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Assessing the effectiveness of on-farm and abattoir interventions in reducing pig-meat borne salmonellosis within EU Member States

As part of the evidence base for the development of National Control Plans for *Salmonella* spp. in pigs for EU Member States, a Quantitative Microbiological Risk Assessment was funded to support the scientific opinion required by the EC from the European Food Safety Authority. The main aim of the risk assessment was to assess the effectiveness of interventions implemented on-farm and at the abattoir in reducing human cases of pig meat borne salmonellosis, and how the effects of these interventions may vary across EU Member States. Two case study Member States have been chosen to assess the effect of the interventions investigated.

Reducing both breeding herd and slaughter pig prevalence were effective in achieving reductions in the number of expected human illnesses in both case study Member States. However, there is scarce evidence to suggest which specific on-farm interventions could achieve consistent reductions in either breeding herd or slaughter pig prevalence. Hypothetical reductions in feed contamination rates were important in reducing slaughter pig prevalence for the case study Member State where prevalence of infection was already low, but not for the high-prevalence case study. The most significant reductions were achieved by a 1- or 2-log decrease of *Salmonella* contamination of the carcass post-evisceration; a 1-log decrease in average contamination produced a 90% reduction in human illness. The intervention analyses suggest that abattoir intervention may be the most effective way to reduce human exposure to *Salmonella* spp.. However, a combined farm/abattoir approach would likely have cumulative benefits. On-farm intervention is probably most effective at the breeding herd level for high-prevalence Member States; once infection in the breeding herd has been reduced to a low enough level, then feed and biosecurity measures would become increasingly more effective.

KEY WORDS: Risk assessment, *Salmonella*, pig, inteventions

1. INTRODUCTION

Campylobacter spp. and *Salmonella* spp. are the two most common causes of foodborne enteritis in the European Union (EU); the latter being responsible for 95,548 confirmed cases in the EU in 2011 [1]. Pigs are commonly infected with *Salmonella* spp. upon entrance to the slaughterhouse and the consumption of pig meat is hypothesized to be a major contributor to human salmonellosis in the EU [2].

The EU implemented a roadmap for reducing *Salmonella* in pigs, with the initial aim of setting reduction targets for pigs at slaughter in each EU Member State (MS), where each MS was expected to put in place a National Control Plan (NCP) in order to achieve reductions. Control programs in several EU MSs are already underway [3,4]; however, the success of most of these programs is questionable. For example, reductions in slaughter pig prevalence were observed that have been related to the Danish surveillance and control program [5] but no further

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reductions were acheived in the years following publication of this study, while other programs in the UK and Germany have so far failed to prove effective in reducing slaughter pig prevalence [3,4]. In addition, it is not a straight-forward task to assign reductions in human cases to a control program due to the natural variation in foodborne cases that would occur regardless of human intervention. Partly due to the lack of knowledge of how to consistently control *Salmonella* on pig farms and in abattoirs, but also the expense required to achieve relatively small reductions in human cases, EU Cost-Benefit Analyses (CBAs) of *Salmonella* control on pig farms and abattoirs did not suggest that National Control Plans would be of cost-benefit [6,7]. Therefore, the EU has currently not implemented legislation to develop NCPs for MSs, but rather has strengthened the microbiological criteria used to monitor the burden of *Salmonella* in the slaughterhouse (European Commission (EC) Regulation 217/2014 of 7th March 2014).

As part of the evidence base for the development of NCPs in individual MSs, a Quantitative Microbiological Risk Assessment (QMRA) was funded to support the scientific opinion required by the EC from the European Food Safety Authority [8,9]. As such, the main aim of this QMRA was to assess the effectiveness of interventions implemented on-farm and at the abattoir in reducing human cases of pig meat borne salmonellosis, and how the effects of these interventions may vary across EU MSs. In this paper, the baseline model described by Snary *et al.* [8] was modified to describe the effect of both on-farm and abattoir interventions and the resultant reductions (if any) on the predicted number of human *Salmonella* cases in an EU MS attributable to pig meat consumption. As with the baseline QMRA model, we investigated four case study MSs: here we present the results from two of these case study MSs (a 'low slaughter pig prevalence' MS1 and a 'high prevalence' MS2) to exemplify the differences that may occur in the effectiveness of interventions between MSs.

The intervention analyses in this paper helped to inform the intervention efficiencies used in the two EU CBAs. If the EU is to meet its aim of reducing salmonellosis attributable to pig meat consumption, then practical interventions (across the food chain) that work consistently and efficiently must be identified. Therefore, the results of this work are still highly relevant to the ongoing discussions regarding how to control *Salmonella* in the food chain.

Table I . Interventions investigated within the analysis

Stage	Description
Farm	Reduction of feed contamination Supplier status Improved hygiene/biosecurity *Within farm*: increased cleaning and disinfection (C&D), longer downtime *External to farm*: prevention of external contamination (via rodents, birds etc... Increased resistance to *Salmonella* infection (e.g. wet feed, vaccination)
Transport	Increased C&D
Abattoir	Reducing/preventing faecal leakage Logistic slaughter (process high-risk pigs at end of day)

2. METHODS

2.1 Interventions investigated

In line with the EU and the EFSA Working Group on *Salmonella* in Pigs we considered many interventions and then prioritized the following specific interventions in Table I .

2.2 Summary of the baseline model

The EFSA QMRA model is a full farm-to-consumption model. The model is described in detail in a series of accompanying papers [10,11,12,13], and an overview is available in Snary et al [8]. It is a stochastic, individual-based (pig/carcass/cut) Monte Carlo simulation model, which explicitly includes natural variability in the introduction, spread, cross-contamination, growth and inactivation of *Salmonella* during the pig meat production chain. The framework is shown in Figure 1. The final output is the predicted number of human *Salmonella* cases per year attributable to consumption of domestically-produced pork chops, minced meat patties and fermented sausages [13]. Here, we investigate the effect of on-farm and abattoir interventions in reducing the number of pig-meat borne human *Salmonella* cases predicted by the baseline model for two case study MSs (MS1 and MS2). These two MSs were picked to be from the extremes of variation in management practices, in order that the intervention analysis would be able to identify the variation in the effect of interventions across the EU.

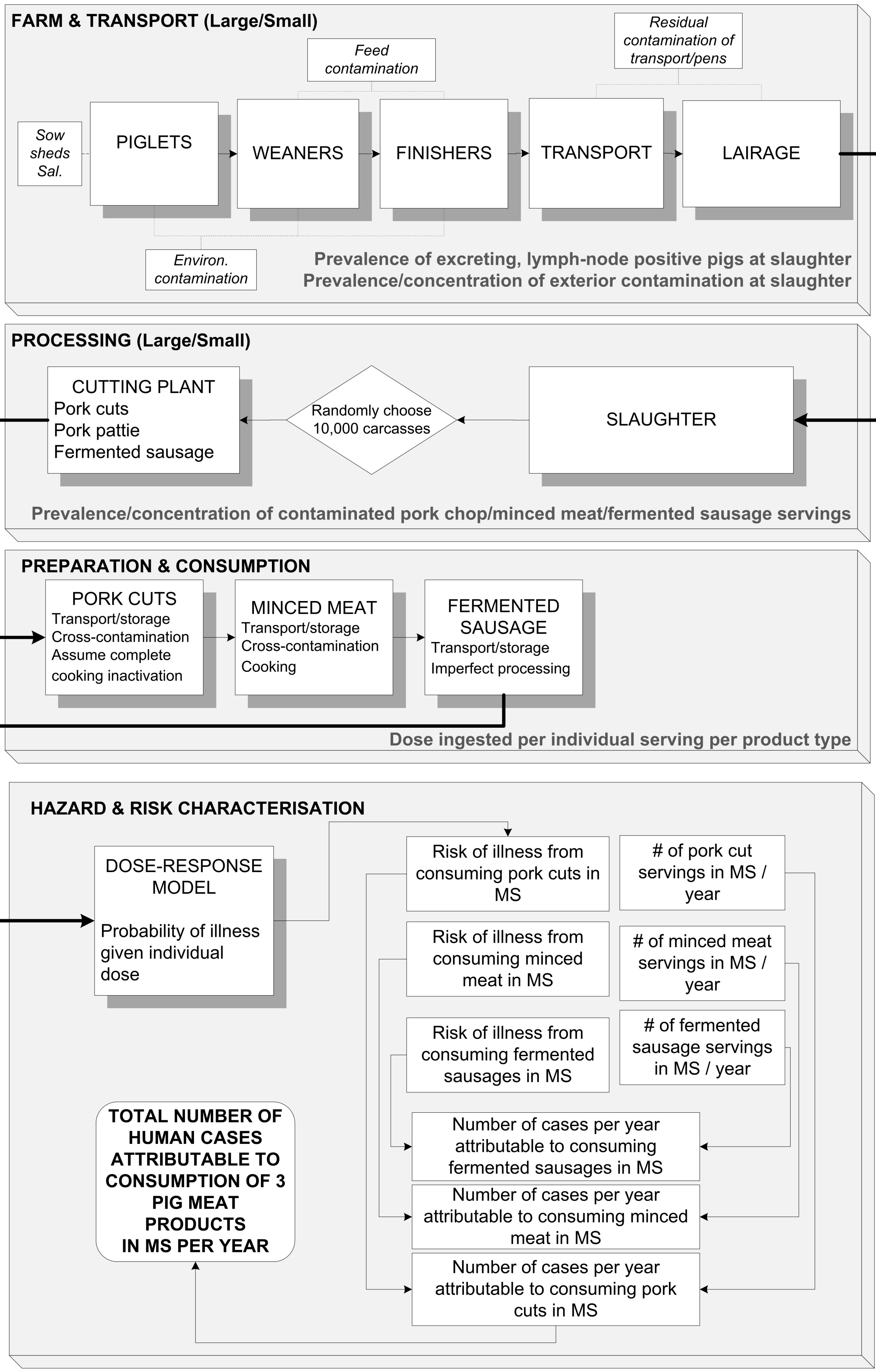

Fig. 1. Model framework for overall EFSA QMRA model. Interventions are modeled by modifying the parameter estimates associated with the farm, transport and abattoir modules.

2.3 Intervention analysis

2.3.1 *Overview*

In general, one of the main benefits of producing a QMRA is the ability to investigate the relative effect of interventions. These relative reductions can be investigated by assessing the percentage reductions in the number of cases observed for each intervention, relative to the baseline model. The farm and abattoir interventions investigated are described in detail in Table II . Each intervention is investigated independently to observe the effect on human illness. It should be noted that QMRA models are not ideal for estimating the absolute burden of human illness, as due to the large number of parameters involved in their construction there is almost always a significant degree of uncertainty surrounding absolute estimates.

Table II . Parameter estimation for the intervention analyses

Intervention	**Baseline parameter estimate(s)**	**Intervention parameter estimates**	Notes
Reduce breeding herd prevalence, p_{herd}	MS1: 0.0595; MS2: 0.44	$\{0, 0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5\}$ for both MS1 and MS2	Range based on results of EFSA baseline breeding pig survey [14]
Reduce slaughter pig prevalence, $p_i(b)$	-	Reduced within-batch infection by s, $s \sim Bin(I(b), p)$, where $I(b) = \#$ infected pigs per batch, $p = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0, 99\}$	Hypothetical what-if reductions.
Reduce feed batch contamination, p_{feed}	0.10	$\{0.01, 0.03, 0.07, 0.1\}$ for both MS1 and MS2	Range chosen based on review of European feed studies [15]
Increased resistance of pigs	$\alpha_{DR} = 0.1766$; $\beta_{DR} = 50235$ (wet feed) or 20235 (dry feed)	$\beta_{DR} = 202,350$ or $2,023,500$	Modified dose-response parameters to achieve hypothetical 1- and 2-log increase in ID_{50}
Increased effectiveness of C&D	Fraction removed from pen, $p_{clean} =$ Beta(3,2) (solid floor - 60% removed) or Beta(1,2) (slatted floor - 30% removed)	p_{clean} modified to Beta(3,50) and Beta(3,500). (solid floor - average 96% and 99.6% removed) (solid floor - average 93% and 99.3% remaining)	1- and 2-log increase in proportion of contamination removed as indicated by [16]
Increased C&D (transport)	Variable reductions (0-7-log CFU)	Additional reductions over and above the original cleaning efficiency (log/day or log/night) χ_L^E of 0.5-, 1- and 2-log CFU.	[16]
Reducing/preventing faecal leakage	Farm model output of contamination level in infected pigs' faeces.	Set contamination level of gut, c, to zero CFU for each infected pig	Hypothetical best-case scenario
Logistic slaughter	Model randomly selects batches [11]	Model randomly selects batches, then sorts selected batches into ascending order of within-batch prevalence, $p_i(b)$	Hypothetical best-case scenario
Decontamination pre-chill, H_7	-	Reduce by 1-,2- and 3-log CFUs.	Hypothetical reductions requested by EU

2.3.2 *Farm interventions*

The results of the farm model[10] suggest that national breeding herd prevalence is a dominant factor in determining national slaughter pig prevalence (i.e. low breeding herd prevalence leads to low slaughter pig prevalence, and vice versa). For the farm model, there are a number of parameters for which there are large differences between the MSs, including the breeding herd prevalence parameter, p_{herd}, and those relating to the structure of the farm industry. We have investigated different breeding herd prevalences within the MS1 and MS2 models. The range of values modeled (0-50%) was chosen to reflect the range of breeding herd prevalence recorded in the four case study MSs (0.06 to 0.44) from the breeder pig baseline survey[14].

In addition to the varying breeding herd scenarios, we also investigated hypothetical reductions in slaughter pig prevalence (independent of any farm/transport/lairage intervention mechanism) from 5-99% of the baseline MS1 and MS2 slaughter pig prevalence. To achieve these reductions we reduced within-batch prevalence (see Table II), as a reduction in the number of infected pigs within a batch, rather than a complete elimination of infection from a batch/farm, would appear a more likely occurrence given the current crop of interventions being suggested at the farm level (e.g. acidified feed, vaccination).

There are no national data to suggest how the prevalence of feedlot contamination (i.e. the percentage of feed batches that are contaminated with *Salmonella*) might be reduced. Therefore, hypothetical changes in the prevalence of feedlot contamination, p_{feed}, were investigated. The original value of p_{feed} (0.10) was changed to one of the following set for another simulation, $p_{feed} = \{0.01, 0.03, 0.07, 0.1, 0.15, 0.2\}$. This range of values was chosen to reflect data that suggest prevalence of *Salmonella* contamination of feed commonly varies between 1% and 10%[15], and the commonly held belief that the sensitivity of feed sampling is low.

There are three ways to incorporate an improvement in biosecurity or hygiene. First, the efficiency of cleaning and disinfection (C&D) (between batches) in removing *Salmonella* can be increased. Second, the inclusion of downtime between batches of weaning, growing and finishing pigs (in the same way as is modeled in the baseline model for farrowing groups[10]) may reduce contamination of the pig pen environment before the repopulation of the pen. Finally, external contamination (e.g. infected rodents, birds) can be prevented from entering the farm. However, as external contamination (via rodent/bird faeces contamination) was both predicted to be of little importance in the analysis of the farm model[10] and rodent control has been identified as relatively expensive to implement compared to other interventions[17], no further investigation of biosecurity barriers was carried out in the intervention analysis.

There are qualitative data that do suggest that cleaning can have a positive effect in reducing *Salmonella* levels within a pen[18]. However, there are few data to quantitatively estimate the differences in *Salmonella* levels before and after C&D. A British experimental study that investigated improvements to standard C&D routines for red meat lairage pens suggested that an extra reduction of 1-2 logs could be achieved over and above typical C&D routines[16]. The baseline model estimate for p_{clean} was based on an expert-opinion-derived beta distribution to describe variability about the efficiency of cleaning. We therefore increased the baseline model reductions achieved by cleaning by an extra 1- or 2-logs (see Table II), that is, we modified the beta distribution for p_{clean} until the average value of the distribution was 90% and 99% lower than the baseline respectively. It was assumed that the main mechanism by which downtime achieves a reduction in *Salmonella* contamination is by the drying out of the pen, which reduces the number of *Salmonella* in the pen environment that are available for carry-over of infection. Assuming that any reduction achieved by drying is independent of any C&D routines applied then a 4 and 7 day downtime between restocking of pens would achieve an additional 0.16- or 0.28-log reduction in contamination of a pen before restocking[19,20]. Therefore, we did not independently model downtime as an intervention, but inferred the effectiveness of this intervention from the hypothetical log reductions we investigated.

Systematic reviews of vaccination[21] and pH/moisture content of feed[22] concluded that there are few studies that are of relevant quality for assessing the effect of reducing *Salmonella* levels in market age pigs. The overall conclusion from the former systematic review was that there does appear to be a positive effect of vaccination in reducing *Salmonella* prevalence in pigs. In addition, the latter study gives a low-confidence assessment that wet feed and acidified feed were effective in reducing *Salmonella* prevalence relative to dry and non-acidified feed respectively. Recent studies on organic acids, not included in these systematic reviews, are also inconclusive on the effect of organic acids in reducing *Salmonella* in pigs at slaughter [18,23,24,25,26,27]. Similar conclusions can also be drawn for non-pelleted feed [22,23,28], where evidence does exist for a positive effect, but few data are available to conclusively prove and enumerate such an effect. An important point missing from all of these studies is the effect of these interventions on the number of salmonellas contaminating the faeces. Given the current dynamics of infection for both pigs and humans modeled in the QMRA model [8], then reducing the shedding load of a majority of pigs may provide better results than preventing *Salmonella* infection in a small percentage of pigs as is typically achieved by current on-farm intervention.

From the above evidence, it was not possible to quantitatively assess the effect of any on-farm intervention in reducing the prevalence in/shedding magnitude of slaughter pigs. However, vaccination, feed and organic acids can all be considered interventions that increase the resistance of the pig to infection. Vaccination boosts the immune response to infection, while introduction of organic acids and wet feed can be considered to alter the gut ecology/microbiology such that *Salmonella* do not survive or multiply as easily within the digestive system (hence reducing the potential for infection). These 'resistance' interventions (vaccination, feed type or organic acid) were investigated hypothetically via modification of the dose response model parameters for slaughter pigs (α_{DR} and β_{DR}, which change the shape of the curve and shift the curve along the x-axis respectively).

The mechanisms for increased resistance are obviously different between vaccination and feed: vaccination stimulates the immune response of the pig, while feed/organic acids change the pH/organic acid make-up of the pigs digestive system, making a less favorable environment for *Salmonella* survival/colonization. However, given that the quantitative effects of each mechanism are not known, it was assumed that the qualitative effect is the same: it takes more *Salmonella* to reach the same probability of pig infection in the absence of the intervention. We therefore chose to shift the dose-response curve along the x-axis, such that the dose required to achieve the median probability of infection (ID_{50}), $p_{inf} = 0.5$, was increased by 1- and 2-logs respectively (see Table II and Figure 2).

2.3.3 *Transport intervention*

As for farm pen cleaning, little evidence is available to suggest the effects of improved cleaning measures at the transport phase. The same study used to estimate the effectiveness of improved C&D on the farm was used to estimate the corresponding effectiveness for abattoir lairage [16]. The results of the tests for commonly-used cleaning techniques (pressure washing and steam washing) are used in the baseline transport and lairage model [11]. However, the most effective cleaning procedure was pressure washing with sanitizer, which had an average 4.5- (± 0.9-)log initial reduction and 5.2 (± 0.5) log reduction after one hour. This is a further 2 log reduction compared to the effect of pressure washing alone. Following these results a further 0.5-, 1- and 2-log reduction in *Salmonella* counts after cleaning of transport and lairage pens were considered, over and above that which already occurs through standard pressure-washing methods modeled in the baseline model (see Table II).

2.3.4 *Slaughterhouse interventions*

Logistic slaughter is the term given to the operation of slaughtering 'high-risk' pigs at the end of the day, and 'low-risk' pigs at the beginning of the day. The theory is that slaughtering batches of pigs that have a low prevalence of *Salmonella* infection earlier in the day will reduce cross-contamination of *Salmonella* from high-prevalence batches. In practice, it may not be possible to always slaughter batches of pigs by ascending order of *Salmonella* prevalence, because of logistics, but also because there is currently no pen-side test that can reliably and rapidly determine the prevalence of infection in pigs immediately before slaughter. In reality logistic slaughter would be carried out via a bacteriological or serological test at the herd level, such that high-risk herds, rather than high-risk batches, are slaughtered at the end of the day.

Although this is a slaughterhouse intervention it is modeled within the Transport & Lairage module [11]. In this analysis a 'perfect' implementation of logistic slaughter was modeled, as the prevalence of a batch as it enters the slaughterhouse can readily be calculated from the farm model output fed into the transport module. As described for the transport

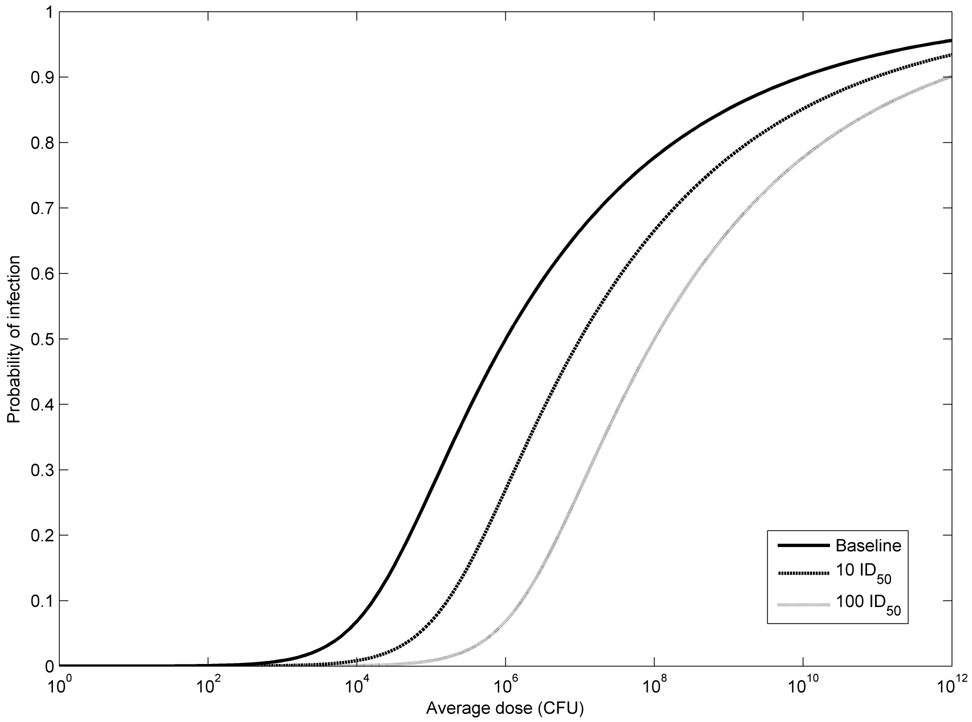

Fig. 2. Dose-response curves for the average probability of infection for the baseline scenario (blue), and two interventions scenarios that lead to a 1-log (green) or 2-log (red) increase in the dose required to cause the same average probability of infection as the baseline dose-response curve.

module the model is set up to randomly pick batches from the farm model output for one day's processing within a random abattoir. The order in which the batches are slaughtered is allocated by ascending order of within-batch prevalence of batch b, $P_i(b)$, such that for each batch slaughtered that day, b_1 to b_n, $p_i(b_n) \geq p_i(b_{n-1}) \ldots \geq p_i(b_1)$.

Decontamination usually takes place immediately after polishing or before (blast) chilling, and can be performed in several ways, for example using water or steam (optionally at high temperatures). Also, a new technique using ultrasound has been used occasionally[(29)]. Irradiation is very effective, but prohibited in the EU, as is adding chemicals. At the request of the EU, the effects of a 1-, 2- and 3-log decrease in exterior contamination were investigated (without defining the specific intervention mechanism), at an individual carcass level, at the point of pre-chill. Pre-chill was chosen as the final practical point along the slaughter line where intervention can occur.

During dehairing and polishing, faecal material may exit via the rectum of the pig. This can also happen before belly opening, after the rectum is loosened. This introduces an extra amount of contamination on the machine and the exterior of the pig. It is common practice in Denmark, Norway and Sweden to seal off the rectum of the pig with a plastic bag after loosening. After polishing, the rectum is circumcised, loosened and bagged, which prevents any further leakage. This intervention is modeled by setting the amount of *Salmonella* within an infected pig's gut, c, to zero (the same parameter is defined as $C_{7,k}$ in Swart *et al.*[(12)]).

3. RESULTS

3.1 Hypothetical reductions

The effect of hypothetically reducing slaughter pig prevalence and breeding herd prevalence on the number of human cases is shown in Figure 3. Reducing slaughter pig prevalence appears to be effective in reducing the number of human cases per year for both case study MSs. Indeed for MS2, which has a high baseline slaughter pig prevalence, there is a strong proportional relationship between reduction in slaughter pig prevalence and reduction in the number of cases. The relationship for MS1 is not as strongly proportional, but there is a distinct downward trend in cases as slaughter pig prevalence is reduced. Breeding herd prevalence has already been established as a significant factor within the farm model, via sensitivity analysis [10]. Broadly speaking, low breeding herd prevalence (low number of positive piglets) suggests low slaughter pig prevalence and vice versa. This intervention analysis produces a similar result.

3.2 Farm and transport interventions

While the mechanisms for removing *Salmonella* are different for downtime and cleaning, the effect is similar: a reduction in the *Salmonella* levels present in a pen at the point where a new batch of pigs enters the pen. However, on average, neither the implementation of improved C&D routines or downtime across all farms within a MS significantly reduced the slaughter pig prevalence or the number of estimated human cases relative to the baseline model.

Modifying the dose-response relationship (via vaccination, organic acids etc. . .) for ALL pigs at ALL stages of production across a MS was an effective measure for both MS1 and MS2. The model suggests that a 1-log increase in ID_{50} when compared to the baseline model produces over a 90% reduction in slaughter pig prevalence and consequently the number of human cases. For both MSs, a 2-log increase in the ID_{50} virtually eliminates *Salmonella* infection in pigs at slaughter.

The effect of eliminating feed contamination completely on national slaughter pig prevalence in MSs 1 and 2 was investigated previously; there was minimal effect in reducing feed contamination in MS2, but slaughter pig prevalence could be reduced by a large margin in MS1 [10]. A similar result was found when investigating the effect on the number of human cases by varying the probability of feed contamination in both MS1 and MS2 models; little reduction is seen in MS2 illness rates, but the model indicates that a large reduction can be achieved in MS1 when feed contamination was significantly reduced (see Figure 4).

The modeled increased cleaning techniques (producing a 0.5-, 1- or 2-log reduction in transport contamination before loading of pigs) had a negligible effect on slaughter pig prevalence and hence the number of human cases, for both MSs 1 and 2.

3.3 Slaughterhouse intervention results

The modeled effect of slaughtering high-risk batches at the end of the slaughter day (logistic slaughter) had a negligible effect on slaughter pig prevalence, and hence also the number of human cases, for both MSs. This is because within the model the vast majority of cross-contamination during processing occurs within the same batch, rather than between batches of pigs [8].

A clear trend was observed when investigating the effects of a 1-, 2- or 3-log decontamination intervention pre-chill, where a reduction of model carcass contamination level of between 1 and 2 logs is sufficient to produce a large (>80%) percentage decrease in the number of human cases within either MS1 or MS2 (see Figure 5). The majority of contamination on the carcass post-singe has been estimated to originate from faecal leakage [12]. Preventing this faecal leakage within the model resulted in an average reduction across all carcasses at pre-chill of roughly 1-log. This resulted in a 80-99% reduction in human cases attributable to pork chop, minced meat and fermented sausage consumption in MS1 and MS2 (equivalent to a 1-log reduction as shown in Figure 5).

4. DISCUSSION

The baseline model of the EFSA *Salmonella* in pigs QMRA [8] has been modified to investigate the varying effect of particular interventions in reducing human illness attributable to pig meat consumption in the EU. The model used to conduct this intervention analysis is unprecedented in the level of detail in which the pig production chain has been modeled. The main aim of the model was to describe the effect of on-farm and abattoir interventions in reducing the number of *human cases* of *Salmonella* attributable to domestic pig meat consumption in the EU. Human *Salmonella* illness is dose-dependent, hence in order to successfully model interventions across the food chain there must be an emphasis on the dose which humans will ingest through pig meat consumption. We have therefore focused most of our efforts in modeling/parameterizing concentrations of *Salmonella* in faeces/on carcasses, and the subsequent doses to which people are exposed. Given that the vast majority of the scientific literature for

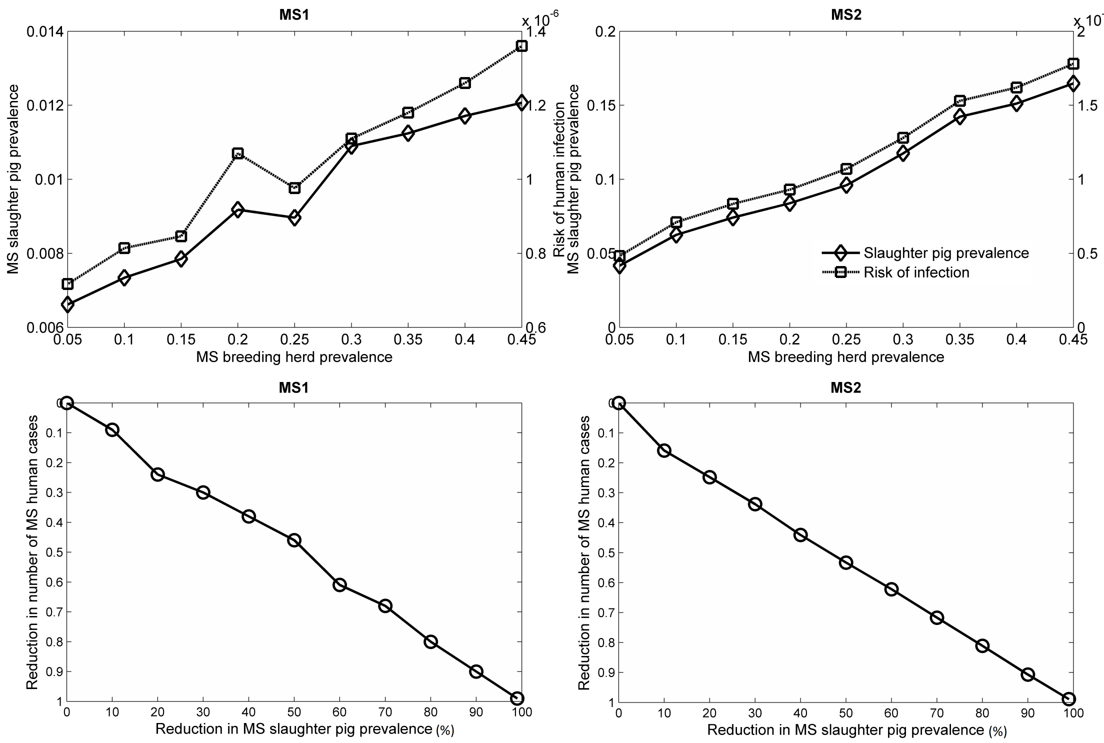

Fig. 3. The top two panels show the effect of varying MS1 and MS2 breeding herd prevalence on the corresponding MS slaughter pig prevalence and risk of human illness. Note different scales of two y axes: slaughter pig prevalence on left hand side (denoted by line marked with circles), and risk (probability) of illness on right hand side (denoted by dotted line marked with squares). The bottom two panels show the fractional reductions achieved in human cases by reducing MS1 and MS2 slaughter pig prevalence - that is a 0.1 reduction equates to a 10% reduction.

Salmonella in pigs measures the prevalence, incidence or proportion of pigs infected/contaminated, then focusing on modeling concentrations and doses limits the available data that can be used for risk assessment modeling. However, despite the attendant uncertainties in doing this, it is our belief that modeling the distribution of concentrations/doses is fundamental to answering whether on-farm or abattoir interventions can produce the goal which the EU requires, a reduction in the number of human cases of *Salmonella* attributable to pig meat consumption.

The results of this intervention analysis suggest that both farm and abattoir interventions could achieve large reductions (up to 99%) in the number of human cases per year in both MS1 or MS2. However, to produce these large reductions then the slaughter pig prevalence and/or the level of contamination at pre-chill must be reduced by approximately ten-fold. It is unlikely that on-farm interventions, implemented on a nationwide scale, can produce such large reductions in slaughter pig prevalence (at least in the short term), but, as shown in this paper, there are abattoir interventions such as anal bunging that have been shown to reduce the average Enterobacteriacae level of pre-chill carcasses by a log or more[30,31].

There are few data to quantitatively assess the impact of relevant interventions such as vaccination, organic acids or feed measures, hence we investigated hypothetical changes in the mechanisms of interventions (e.g. reducing the amount of environmental *Salmonella* contamination that would remain in the pig pen environment after improved C&D procedures). In addition, in order to implement any of the interventions, two critical factors were assumed: that uptake of each intervention is 100% across all farms/slaughterhouses across a MS; and that all farmers/hauliers/slaughterhouses would rigorously implement interventions in such a way as to consistently produce the effect desired (e.g. reducing carcass contamination by 1-log). Given the above assumptions and lack of data, it was not possible to identify specific interventions that

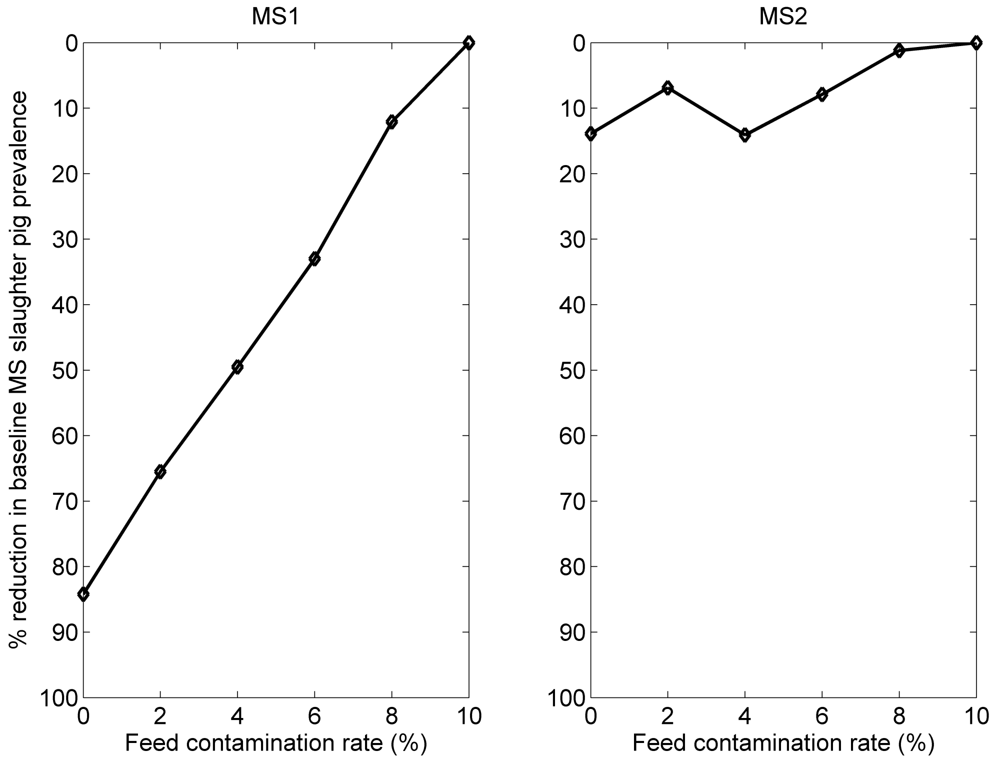

Fig. 4. The effect on MS slaughter pig prevalence by varying the prevalence of feed contamination.

will achieve large reductions (with the possible exception of anal bunging) in human cases, but it was possible to identify which mechanisms of intervention (reduce contamination of environment/feed, increase resistance of pig, prevent contamination of carcass or decontaminate it at abattoir) that are more likely to be effective. Given the intervention analysis results, which suggest reasonably proportional relationships between reductions in pig prevalence and slaughter pig prevalence/human cases, a decrease in uptake below 100% would result in a similar decrease in the effectiveness of the intervention on slaughter pig prevalence/number of human cases.

Reducing slaughter pig prevalence is effective in reducing the number of human cases per year for each case study MS, as reductions in pig infection follow through the food chain and result in reduced human illnesses (Figure 3). A main conclusion from the same figure is that reducing breeding herd prevalence is a strong indicator for slaughter pig prevalence[(10)], which in turn is a strong indicator of the number of human cases. Hence, by reducing breeding herd prevalence, major reductions in the number of human cases could be achieved. As identified in the farm model sensitivity analysis[(10)], the most important factor that determines the MS slaughter pig prevalence was the concentration of *Salmonella* in the sows' faeces (which then subsequently exposes piglets to infection). Therefore, the most effective method to reduce slaughter pig prevalence would appear to be to reduce the number of infected piglets entering the weaning stage. Only once the total burden of infected piglets entering the weaning stage is reduced to levels similar to those in MS1 do feed and external sources of contamination (e.g. rodents) become more important (Figure 4). This does therefore suggest that if breeding herd prevalence is high it should be controlled as a priority. Feed and external contamination of finishing pigs can then have a positive effect once breeding herd infection is reduced to low levels (current model predictions suggest below 5-10%).

A more extensive discussion of the role of the sow as a source of infection is given in Hill *et al.*[(10)]. Briefly, the extent of the role of the sow as a source of infection for slaughter pigs is uncertain, although longitudinal studies do

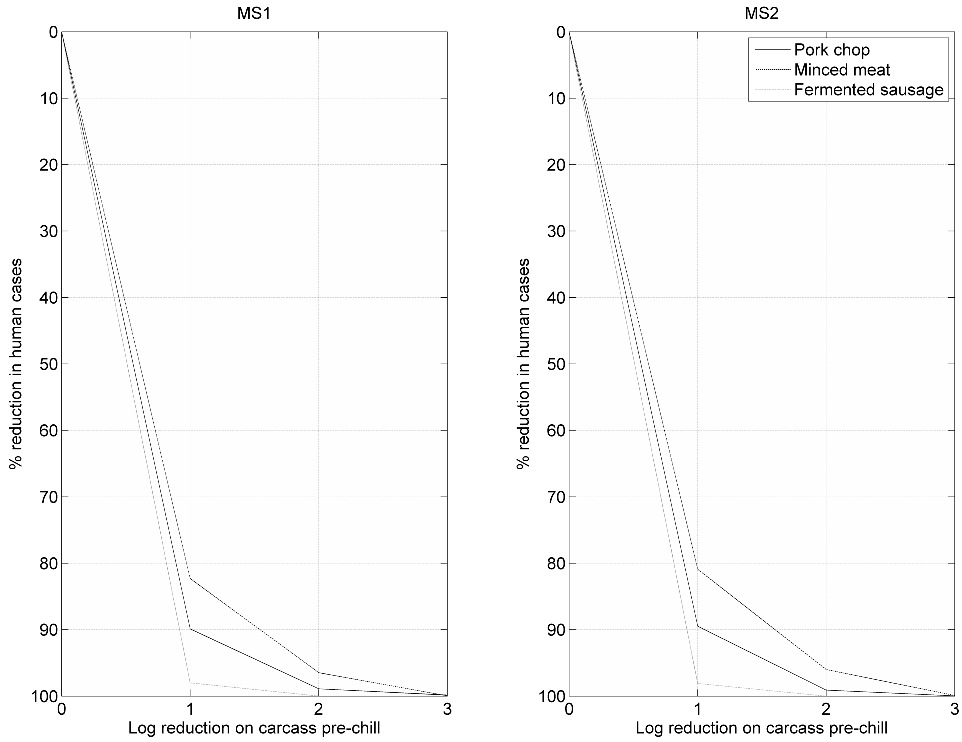

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Fig. 5. Percentage reductions in MS human cases per year by applying a blanket 1-, 2- and 3-log decontamination event pre-chill across all pigs slaughtered in MS1 and MS2.

suggest that sows are commonly infected with the same strain of *Salmonella* as piglets/weaners within the same cohort[32,33], and recent analysis by EFSA shows that there is a correlation between MS breeding herd prevalence and MS slaughter pig prevalence[34]. The dynamics of infection are complicated by the presence of multiple strains on farms causing intermittent infections, which is inadequately captured by insensitive sampling methods. Evidence also exists for strains persisting in the weaning/finishing herd environment, which exposes susceptible pigs to challenge long after they have been weaned[33]. To summarize, the model results suggest that intervening at the breeding herd is a necessity if slaughter pig prevalence is to be reduced substantially; however, further studies on the link between sow infection/environmental contamination and slaughter pig infection is required to firmly establish the links that exist at a farm and MS level.

Of all the on-farm intervention mechanisms investigated only increasing the resistance of the pig to infection produced a reduction in human cases for both MSs. Modifying the dose-response model by 1-2 logs produces a significant effect in reducing slaughter pig prevalence and human illness. The effect modeled is by a constant modification of the dose-response relationship, and hence current intervention trials where the application of organic acids or vaccination is applied only over limited time frames are unlikely to achieve similar reductions in slaughter pig prevalence. Therefore, more promising interventions may be changing feed type (as this can be applied over all post-weaning stages) and/or applying organic acids over the whole course of production. However, several systematic reviews have noted that there is not enough evidence to state with any confidence the likely effect of these interventions if universally adopted by pig industries across a MS[21,22]. Reducing feed contamination is only likely to have a measurable effect on slaughter pig prevalence when the transmission of *Salmonella* from pig to pig has been brought to a low level, as in MS1. As for all interventions modeled here, the magnitude of effect that can be achieved in reality is very uncertain, given that it is not known what the prevalence or contamination levels of feed are across the EU.

The modeling of C&D interventions, whether on the farm, during transport or in lairage appear to suggest that intervention in this ay is relatively futile. Both extra C&D and logistic slaughter did not achieve any observable decrease in the number of human cases, in either MS1 or MS2. However, we have implicitly assumed an effective standard of C&D as a default for the transport and lairage models; therefore potential gains may be achieved if C&D procedures are not already sufficient. As discussed in more detail elsewhere [8], the modeled level of cross-contamination in the abattoir is not significant in terms of causing extra human illnesses, hence the characteristic which logistic slaughter attempts to address (cross-contamination) contributes to a negligible decrease in the number of human illnesses.

Marked reductions ($>$ 90%) can be achieved by applying a pre-chill decontamination measure that can consistently achieve a 1-log reduction in carcass contamination. Consistently and effectively bunging the anus of each pig achieves a similar 1-log reduction in carcass contamination, and hence is equally as effective in reducing human cases. Non-chemical interventions have already been shown to produce reductions in enterobacteriacae of the order of 1-2-logs [30,31], and hence could be a viable short-term measure for reducing illness in humans, if they are shown to be as effective when scaled up to be applied across all a MSs slaughterhouses. However, these intervention measures at the abattoir do not reduce any burden of illness caused by the indirect transmission of *Salmonella* from the pig farm (e.g. contamination of lettuce via manure spreading), whereas on-farm intervention could also decrease this mode of exposure.

A comprehensive review of *Salmonella* in pigs [2], which explored possible interventions across the farm-to-fork pathway, concluded that it was not possible to control *Salmonella* with the adoption of just one measure. In other words, the control of *Salmonella* can only be achieved by the introduction of multiple interventions across the farm-to-consumption pathway. While the effects of multiple interventions will accumulate, it would not be expected that the effectiveness of interventions would be additive or multiplicative (i.e. the effectiveness of two interventions, denoted a and b, does not equal $(a + b)$ or ab), due to the complexity of the pig production chain and various interactions and feedback loops. Analysis carried out on multiple interventions (but not published here) shows that careful consideration needs to be applied when choosing the interventions to implement across the food chain, as some combination of interventions (e.g. two modestly effective on-farm interventions) may produce an effect greater than the sum of its parts, while in other circumstances the effect of multiple interventions is completely dominated by one intervention (e.g. anal bunging in conjunction with finishing feed interventions in MS1). Not only is there an issue with deriving the maximum effectiveness in reducing human illness from the interventions, there is also the issue of deriving the maximum cost-effectiveness of interventions. For example, anal bunging alone is probably more cost-effective than a combined anal bunging/feed intervention program.

It is very difficult to validate such intervention results, as by its very nature this risk assessment model has been developed because there are no real-world data to assess the effectiveness of on-farm and abattoir interventions in reducing human illness. Data from the scientific literature can be used to assess relationships between two or more intermediate steps between intervention and human illness. However, much of the data in the literature only compares the difference in prevalence of infection/contamination between controls and interventions, which limits these studies' applicability for validation of the model, given we are more interested in validating the change in the distribution of concentrations in faeces/on carcasses/doses. A general discussion on the validation of the baseline model dynamics can be found in [8], which may also be of relevance.

Uncertainty in the baseline model is described by Vigre *et al.* [35]. The main conclusions from this uncertainty analysis was that much of the uncertainty could be attributed to the Preparation & Consumption stage, an expected result given the lack of appropriate data to model people's behavior while preparing food. However, a number of variables in the modules where interventions have been modeled (farm, transport and abattoir) are shown to be both uncertain and important in driving the final risk value: the probability of feed contamination, probability of reverting to shedding during transport and the transfer of faeces from pig to dehairing machine during processing of the carcass. The probability of feed contamination has also been investigated with the same result: it is important once highly-shedding pigs are reduced and the relative importance of feed is increased (e.g. in MS1). The other two variables are indicators of the amount of *Salmonella* in the production environment (rather than indicators of prevalence of infection). This is logical given we predict that it is the presence of "super-shedding" pigs (shedding more than 10^4 CFU/g faeces) that drive the risk of human illness; other factors, such as cross-contamination within the abattoir, were estimated to be minor contributors in comparison [(8)]. Super-shedding pigs may contribute up to 100-10,000 times the numbers of salmonellas into the farm or processing environment than the majority of infected pigs [(10)]; therefore the vast burden of *Salmonella* that resides on retail cuts of pig meat is generated by these super-shedding pigs.

We are confident that the general results of the intervention analyses are robust, as the uncertainty analysis simply identifies changes in the absolute numbers involved but does not readily alter the relative change in the reductions achieved by interventions. Despite the extreme differences in the modeled faecal shedding rate of individual pigs (infected pigs may shed between 0-10^8 CFU/g faeces [(36,18)]) there is still, once averaged out over a MS, a strong proportional relationship between breeding herd prevalence and slaughter pig prevalence, and between slaughter pig prevalence and risk of human illness. Therefore, we would expect that any uncertainty introduced around the shedding rate (which would probably contribute at most an extra 1- to 2-logs to the variance of shedding rate) would perhaps change the absolute values of the risks, but not disrupt the proportional relationships found in the analyses of the baseline model and the intervention analyses presented here. What may change the results of the model would be a different overall conclusion about the shape of the shedding distribution, where for example fewer super-shedders may lead to an increased effect of cross-contamination, and therefore distupt the proportional relationship between slaughter pig prevalence and risk of illness. While this cannot be ruled due to the small datasets available to model the distribution of shedding by individual pigs, given knowledge of how enteric bacteria colonise animals it would be biologically unexpected to not have at least some natural super-shedders.

A similar explanation as above can be given for the reason why C&D, at any stage of the production chain, does not appear to be effective at all in reducing human illness; C&D removes salmonellas from the environment, such that they cannot be cross-contaminated to the pigs/carcasses. However, the level of environmental contamination (at the farm or during transport, lairage or processing) is typically orders of magnitude less than contamination of the faeces of super-shedding pigs, such that the majority of salmonellas found on pig meat that proceed to cause human illness are derived directly from the pigs that produced that meat, and further that those pigs were infected by from salmonellas shed by their own cohort of pigs.

Cross-contamination can and has been shown to occur in the abattoir, and our baseline model results readily agree with an estimate that 20-30% of contaminated carcasses at chill originate from resident flora rather than contamination from the pigs being processed [(37)]. However, most studies do not include the magnitude of cross-contamination, which means that the relevance of cross-contamination in the lairage or in the abattoir to the burden of human illness cannot be gauged. The model predicts that the magnitude of cross-contamination is low, such that the contamination level of cross-contaminated carcasses is beneath that required for a high probability of human illness. Further studies are required to investigate the magnitude of cross-contamination to confirm or refute the model results, including the proportional relationship between slaughter pig prevalence and human illness and the ineffectiveness of logistic slaughter/C&D.

Given a lack of data to state otherwise, we have assumed that the rate of uptake and compliance with any farm or abattoir intervention introduced as part of a NCP will be 100%. Previous control programs have shown that this would be extremely unlikely. The effectiveness of on-farm interventions is particularly variable. The uptake and compliance rates are likely to depend on the cost and ease with which they can be introduced, which has not been factored into these intervention analyses, but these issues must be considered when MSs choose interventions for their NCPs. The results of these intervention analyses were used as part of two EU cost-benefit analyses for breeding and slaughter pig intervention [(6,7)]. Only in the most optimistic scenarios was there a cost-benefit to intervention, largely because the numbers of human *Salmonella* illnesses that can be attributed to pig meat consumption is low compared to poultry and egg consumption.

From the current evidence, it would appear that specific slaughterhouse interventions are, at present, more likely to produce greater and more reliable reductions in human illness, at least in a shorter time frame than can be achieved at the farm. However, the hypothetical reductions and multiple interventions investigated with the current risk assessment model suggest that MSs can still achieve reductions in human cases by on-farm interventions, but much more research is necessary before consistently effective on-farm measures can be identified.

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