**Understanding the role of global food trade on the transmission dynamics of antibiotic-resistant foodborne bacteria**

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**ABSTRACT**

**INTRODUCTION**

1. Resistance is a big issue – specifically the resistance that might occur from livestock.
2. This is part of this one health issue – with studies often exploring the impact of transmission from livestock
3. However transmission from livestock is a multifaceted issue – transmission can come in the form of direct contact with domestic livestock, food products from domestic sources, but also from imported sources
4. Note some studies which have done this – the Ludden et al study as an example – which sampled food products from local supermarkets which obviously have food products from imported sources
5. But also mentioned that this often is not done – there needs to be more of an emphasis to explore the heterogeneity in terms of AMR transmission from livestock populations – to stratify the livestock population into both imported and domestic
6. This is important considering the implications of having heterogeneity in terms of transmission pressure – for example – give examples of other mathematical models showing that heterogeneity in terms of transmission pressure
7. This is therefore also the case in terms of AMR in a one health context – many reviews have stated that to understand AMR mechanistically from a modelling POV – we need to understand how the different sources of AMR might also contribute to AMR transmission
8. One such example is understanding how import of AMR on food products from different sources may also impact AMR transmission to humans – especially from livestock
9. This is an important aspect to consider considering a slow increase in food products over the next few years – the increase in the population requiring food to be imported
10. A likely reliance on imported food – and Brexit signing deals with countries with less than stellar food safety records
11. Means it makes sense to explore the impact of imported food products on the overall dynamics
12. We seek to explore the effect of heterogeneity in transmission pressure from livestock populations through the use of a compartmental metapopulation type model where we try to understand the impact of stratifying livestock antibiotic usage
13. We try to understand the impact on the impact of interventions such as the effect of curtailing livestock antibiotic usage when there is an import fraction.

**METHODS**

**Model Structure and Parameters**

A compartmental model was developed to describe the transmission of antibiotic-resistant and antibiotic-sensitive *Salmonella* spp. from domestic and imported livestock food products to humans (**Figure 1**). Salmonella transmission dynamics were modelled explicitly for domestic livestock and human populations, with each modelled population stratified based on their respective infection status: susceptible humans (SH), humans infected with antibiotic-sensitive bacteria (ISH), humans infected with antibiotic-resistant bacteria (IRH), susceptible livestock food-animals (SA), livestock food-animals infected with antibiotic-sensitive bacteria (ISA) and livestock food-animals infected with antibiotic-resistant bacteria (IRA).



**Figure 1. Model structure describing the transmission of foodborne pathogens between/within livestock and human populations.** Model equations and parameters can be found described in the supplementary material ().

The influence of imported food products was modelled as a constant transmission pressure to human populations. The proportion of imported food products contaminated with either antibiotic-resistant Salmonella spp. was modelled as a function of the proportion of contaminated food products that are antibiotic-resistant (PropResImp) and the proportion of food imports contaminated with Salmonella spp. (FracImp). The proportion of food imports contaminated with antibiotic-sensitive bacteria follows the same calculation bar the use of (1-PropResImp).

Two transmission routes of antibiotic-sensitive/resistant Salmonella spp. were modelled, with domestic livestock-to-livestock transmission (βAA) and transmission from contaminated domestic/imported livestock carcasses/food products modelled (βHA). This βHA parameter represents either direct transmission from the carcasses or through food borne transmission after further processing in the farm-to-fork pathway. Both human-to-human and human-to-animal transmission routes were not modelled due to the focus of the study on the transmission dynamics of foodborne transmission of Salmonella spp. and the negligible role of both pathways on the foodborne transmission of the pathogen ([Infection with Salmonella (cdc.gov)](https://www.cdc.gov/training/SIC_CaseStudy/Infection_Salmonella_ptversion.pdf)). A η scaling parameter was used to transform the proportion of antibiotic-sensitive/resistant carriage in livestock to the extent of Salmonella spp. contamination on livestock carcasses. This scaling parameter represents the decrease in the proportion due to processing steps in the farm-to-fork pathway.

A background rate of transmission in the livestock population was also modelled to represent infection of livestock hosts from non-livestock sources (ζ). This transmission rate was scaled by a factor of 0.5 to ensure an equal influence of ζ on both antibiotic-sensitive and resistant transmission routes. Natural recovery from antibiotic-sensitive/resistant infection occurs in both human/livestock populations at rate rH and rArespectively. Per capita birth/death rates are represented by µA in livestock and µH in human populations.

A parameter (τ) was used to describe the selective pressure and therapeutic effect of antibiotic usage in domestic livestock. The selective pressure of livestock antibiotics was modelled as a single transition rate, encompassing a range of evolutionary and biological phenomena that convert livestock between antibiotic-sensitive to resistant states. Similarly, a single reversion parameter (φ) was used to encompass a range of different biologically plausible phenomena that may cause reversion of antibiotic-resistant (IRA) to sensitive strains (ISA). **A description of these biologically plausible phenomena can be found in the methodology for chapter 2.** The relative proportion of human food usage from domestic sources was modelled as a ψ parameter, with 1-ψ representing the extent of human food products sources from imported non-domestic sources.

To explore the effects of import heterogeneity on antibiotic-sensitive/resistant Salmonella spp. transmission dynamics, the import pressure (FracImp, PropResImp) was stratified into separate transmission pressures, representing different countries that constitute the food trade network in the domestic country (**Figure 2**). Each of these transmission pressures from importing countries requires individual parameterisation with regard to the extent of contamination on imported food products (FracImpX ϵ [FracImp1, …, FracImpX]) and proportion of contaminated food products that are antibiotic-resistant (PropResImpX ϵ [PropResImp1, …, PropResImpX]).



Figure 2. **Model structure describing the transmission of foodborne pathogens between/within livestock and human populations in the model with increased import heterogeneity.** Model equations and parameters can be found described in the supplementary material ().

The increased heterogeneity in import pressure also requires the addition of another set of parameters detailing the relative share that each importing source contributes to the overall importation to the domestic country of interest (ShareX ϵ [ShareFRA, …, Share10]). The real world equivalent of this parameter can be conceptualised as the proportion/contribution of individual importing countries to the overall import of food products to a domestic country of interest.

**Ampicillin usage/resistance in Fattening Pigs Case Study**

The United Kingdom was chosen as the “domestic” country of interest for the model. Therefore, the compartmental model, including dynamic livestock and human populations were parameterised with regard to UK livestock/human outcome measures. The bug/drug/livestock population of interest was modelled as ampicillin usage/resistance in fattening pigs. This case study was chosen due to the high level of usage (both historical and current) of ampicillin in fattening pigs, and the availability of resistance data for this livestock species.

**Efficacy of Curtailment Outcome measure**

The primary outcome of interest for this study was the relative change in proportion of antibiotic-resistant human salmonellosis upon domestic livestock antibiotic. We term this percentage reduction in the proportion of antibiotic-resistant human salmonellosis as the efficacy of curtailment (EoC) (eqn 1.1).

Eqn 1.1

This outcome measure is calculated at the long-term model non-zero steady state. Studying the system at an equilibrium state is a useful indication of the long-term dynamics of antibiotic-resistant salmonella infection and the long-term trajectory of the system. However, we recognise that the “real-world” dynamics of AMR are not temporally stable and in flux.

**Data Sources and Model Fitting**

An approximate Bayesian computation sequential Monte Carlo (ABC-SMC) approach was used to fit the model to the ampicillin usage/resistance in fattening pigs case study, using the United Kingdom and the representative domestic livestock/human populations. This required the curation of three different datasets.

A usage/resistance dataset was curated to parameterise the relationship between livestock ampicillin usage and the proportion of ampicillin-resistant Salmonella spp. carriage. The proportion of isolates resistant to ampicillin from carcasses of fattening pigs was extracted from the respective European Food Safety Authority (EFSA) summary reports (**cite**). Ampicillin sales data was obtained from European surveillance of veterinary consumption (ESVAC) reports. A scaling calculation was required to convert the generic ampicillin sales for livestock to a value specific to fattening pigs with sales described as grams per population correction unit (g/PCU). Details of this can be found in the supplementary information for chapter 2. Note that due to a lack of accurate country-level antibiotic usage data, sales were assumed to be a proxy for usage.

Import Dataset

A dataset was next curated using data from UK Department for Environment & Rural Affairs (DEFRA) data. The relative contribution of UK domestic, EU and non-EU countries that contribute to the UK’s food product consumption was determined from DEFRA data to parameterise ψ and ShareX parameters. This was further stratified into ten major UK food trade partners using data from DEFRA.

Using data on the UKs major livestock-origin food products trade partners, data was sought regarding the

Data on the UKs major trading food trading partners was used to

Scaling calculations were required to determine the relative contribution of ten of the UKs major food import trade partners for

Both the general usage and pig case study

The import dataset was used to parameterise the share of imports, level of contamination and resistance from importing countries for the UK dataset. Using DEFRA data on the UKs major food importing trade partners the proportion of the UKs food supply from domestic, EU and non-EU sources was determined. The share of import from EU and nEU countries was further broken down into 10 regions with xx, …, xxx countries and nEU treated as part of a heterogenous import transmission pressure.

* DEFRA has data on the relative share of Domestic vs EU vs nEU countries on the UK’s food supply.
* However this is for general food products not specific to livestock origin food products – therefore it must be scaled for livestock food products (excluding things like vegetablexss and processed food imports)
  1. We note that two cases tudies were explored to explore the effect – general livestock food products (psi = 0.656) and pig carcasses (psi = 0.4545)
  2. It is important to note that while pigs are the case study chosen by this study – the general import proportions were used to have a fairer repsentation of nEU imports (perhaps need to justify this decision better)
* We therefore generated the proportion of UK food supply for general livestock food products – including poultry, beef, pork and eggs – from EU and nEU countries (rest of the world) – by determiniung the dressed weight and using thgis to generate the propiortioons
* We exclude milk
* We also have data on the share of imports in the UKs EU trade partners – by lookinga tht eproportion of money spent on iumports for the UK
* We can then use the difference between the official reportsz for all food products and the ones for livestock food products and scale these EU importing countries approiately.

We use information from the eCDC and the EFSA to parameterise the levekl of resistance and contamination for each importing country.

* Information was available from competent authorities (CAs) representing official food surveillance programs and fromfood pbusiness operator (FBOp) – surveillance and testing from the pirvate companies who producing the food.
* It is important to note that where possible values from competent authorities were prefereed – however, this likely represents a more pessimistic view on the level of contamination as the average level of contamination across CAs are higher than for FBOp
* Additionally where possible data on the level of contamination from imported food products was satndardised by only taking data from swabs oif 400cm2.

Data for resistance was taken from EFSA data for each country for ampicillin resistance in salmonella in each importing countries. It is important to note that both contamination data and resistance data while obvtained from different surveillance sources – both types of data were obtained from fattening pig carcasses.

**UK Dataset**

The United Kingdom was chosen as the domestic country of origin, therefore data was collected from ecdc and efsa data regarding the level of contamination/incidence of salmonellosis and resistance for both domestic livestock and human populations.

The baseline UK ampicllin usage for the ampicillin-resistnce in fattening pigs case study was considered the unweighted average ampicillin usage observed across 2015-2019 – 0.0009 g/PCU.

Data was obtained from X paper ([Abattoir-based study of Salmonella prevalence in pigs at slaughter in Great Britain | Epidemiology & Infection | Cambridge Core](https://www.cambridge.org/core/journals/epidemiology-and-infection/article/abattoirbased-study-of-salmonella-prevalence-in-pigs-at-slaughter-in-great-britain/3FDEA88F8CF084908FC34C7A6A57052E)), which identified a prevalence of Salmonella spp. found in the caecum of pigs of 32.2%. We also identify a UK level of contamiantion on pig carcasses of 2.865%, representing a reduction in the proportion of 89%. We use this value to parameterise the eta parameter.

* Specifically the removal of certain datapoints because they were unrealistic (where it was just 45/45 resistant), the fact that we used 3 years worth of data (2015, 2016, 2017, 2018) – although one of these intermediate years aren’t available

**ABC-SMC Model Fitting**

A simulated dataset for the ampicillin usage/resistance in fattening pigs case study was generated by modelling the proportion of ampicillin-resistant livestock carriage for each country/year observation, for each of the observed levels of antibiotic sales included in the dataset. A sum of squared errors distance function was then used to calculate the distance between the simulated and observed fraction of antibiotic-resistant livestock infection for each country/year data point. In accordance with the EFSA methodology, countries with <10 isolates in the respective EFSA dataset for a particular year were omitted from the dataset

Four additional summary statistics were used in the fitting approach: 1) minimise the difference between the modelled daily EU incidence of human salmonellosis at baseline antibiotic usage and the observed ECDC daily EU incidence of human salmonellosis currently observed (0.593 per 100,000), 2) minimise the difference between the model estimated proportion of resistant human salmonellosis at baseline antibiotic usage and the EFSA averaged European proportion of resistant human salmonellosis specific for each case study, 2) minimise the difference between the model estimated prevalence of *Salmonella* spp. contamination on swine carcasses and the value observed in ECDC surveillance data and 4) minimise the difference between the model estimated proportion of *Salmonella* spp. livestock carriage that is ampicillin-resistant and the proportion observed in EFSA averaged data.

The ABC-SMC approach was used for both study models (Figure 1,2) to fit the model to available epidemiological data. For the first model, the ABC-SMC approach was used to estimate the marginal posterior probability distribution for six model parameters given the data, . Use of the second model required the estimation of the marginal posterior probability for nine model parameters. Other model parameters were not fitted as estimates with high levels of certainty were available (rH, rA, μA and μH). Prior distributions for each fitted parameter can be found in the supplementary material (Table S4).

The ABC-SMC model fit was run for eight generations, with each generation running until the acceptance of 1000 particles. Acceptance thresholds for each distance measure and summary statistic (ε) can be found in thesupplementary material (Table S5). A multivariate normal distribution was chosen for the ABC-SMC perturbation kernel. The randomly sampled mean and covariance matrix was calculated from the previously accepted generation of accepted particles. An intersection metric was used to ensure that accepted particles satisfied tolerance values set for the distance measure for each calculated for each summary statistic per generation.

Mean point estimates from the approximated marginal posterior probability distributions of the 8th accepted generation were used as the final parameter sets for each respective case study. Point estimates and calculated 95% HDIs from the marginal posterior distribution for each model parameter can be found in the supplementary material (Table S3).

**Sensitivity Analysis**

Latin-hypercube sampling partial rank correlation coefficient (LHS-PRCC) and extended Fourier amplitude sensitivity test (eFAST) approaches were used to conduct sensitivity analyses on both study models (Figure 1, 2) with regard to the efficacy of curtailment outcome measure. Supplementary sensitivity analyses were also conducted to identify important parameters regarding the incidence of human Salmonellosis and the proportion of ampicillin-resistant human salmonellosis outcome measures. Monotonicity analyses were performed for model parameters to identify potential non-monotonicities before conducting LHS-PRCC analyses. The parameter range chosen for the sensitivity analysis was limited to an order of magnitude above and below the fitted mean point estimate for each model parameter.

**RESULTS**

**Section 1**

**Result 1 – Basic model output of withdrawing antibiotic usage and the model fit**

* Supplementary material show the effect of psi on the model output
* Supplementary analysis - General sensitivity analysis plots – mention here – also mention that we do monotonicity plots – mention that we do an LHS PRCC and a eFAST analysis with the general model fit.
* Diagnostics for the all four of the
* What the model fit looks like without import – fit the model without import and identify the model fits and the closeness to the outcome measure – see if there are qualitative differences when we change antibiotic usage

We plotted the model fit for the ampicillin-resistant salmonella in fattening pigs case study. We identified a X fold increase in the incidence of human salmonellosis (baseline and curtailed incidence). We also note a X fold decrease the proportion of the ampicillin-resistant human salmonellosis when livestock antibiotic usage is curtailed. This results in a baseline efficacy of curtialment of 7% (supplementary material – original methods plot)).

* Ampicillin usage is curtailed from a baseline level of 0.0009 g/PCU, resulting in a reduction of the proportion of salmonella infections that are ampicillin-resistant from a baseline value of X to a value of X. This results in an Efficacy of Curtailment (EoC) of 7%.

We note that the average level of contamination and resistance in imported food products was parameterised as higher (what it is for imports) than the fitted domestic level of contamination (prevalence x eta) and resistance (what it is for domestic). We note that increasing the decreasing the level of UK food products ffrom domestic sources in line with the UK pig supply, results in an overall X-fold increase in foodborne disease compared to the baseline scenario (**SUPPLEMENTARY**).

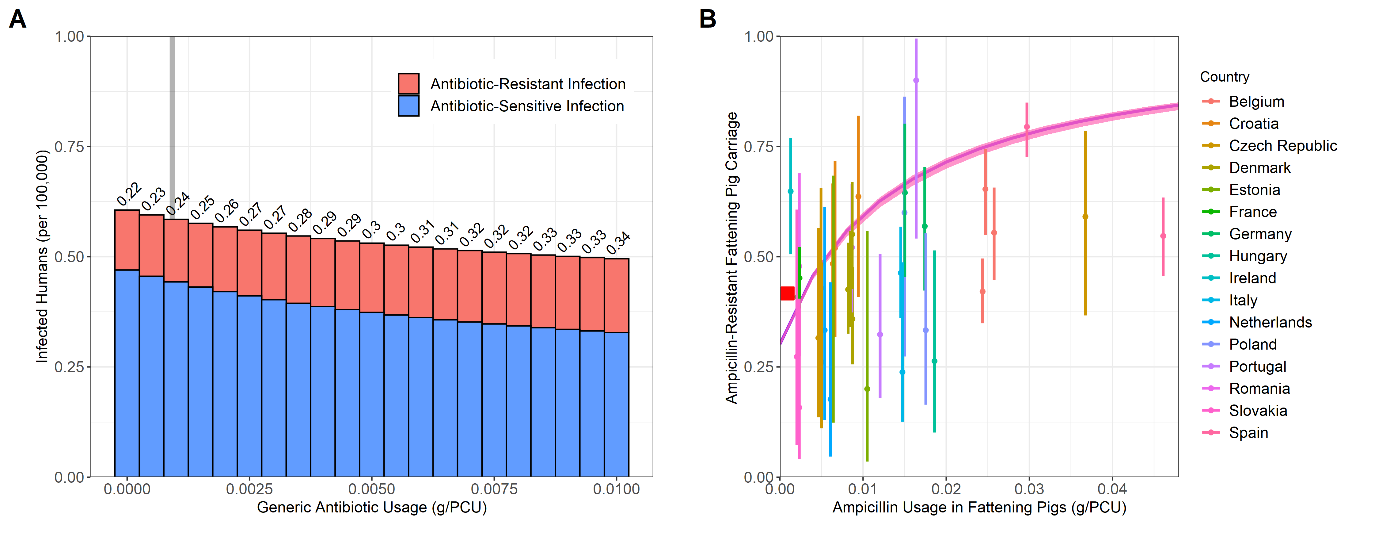


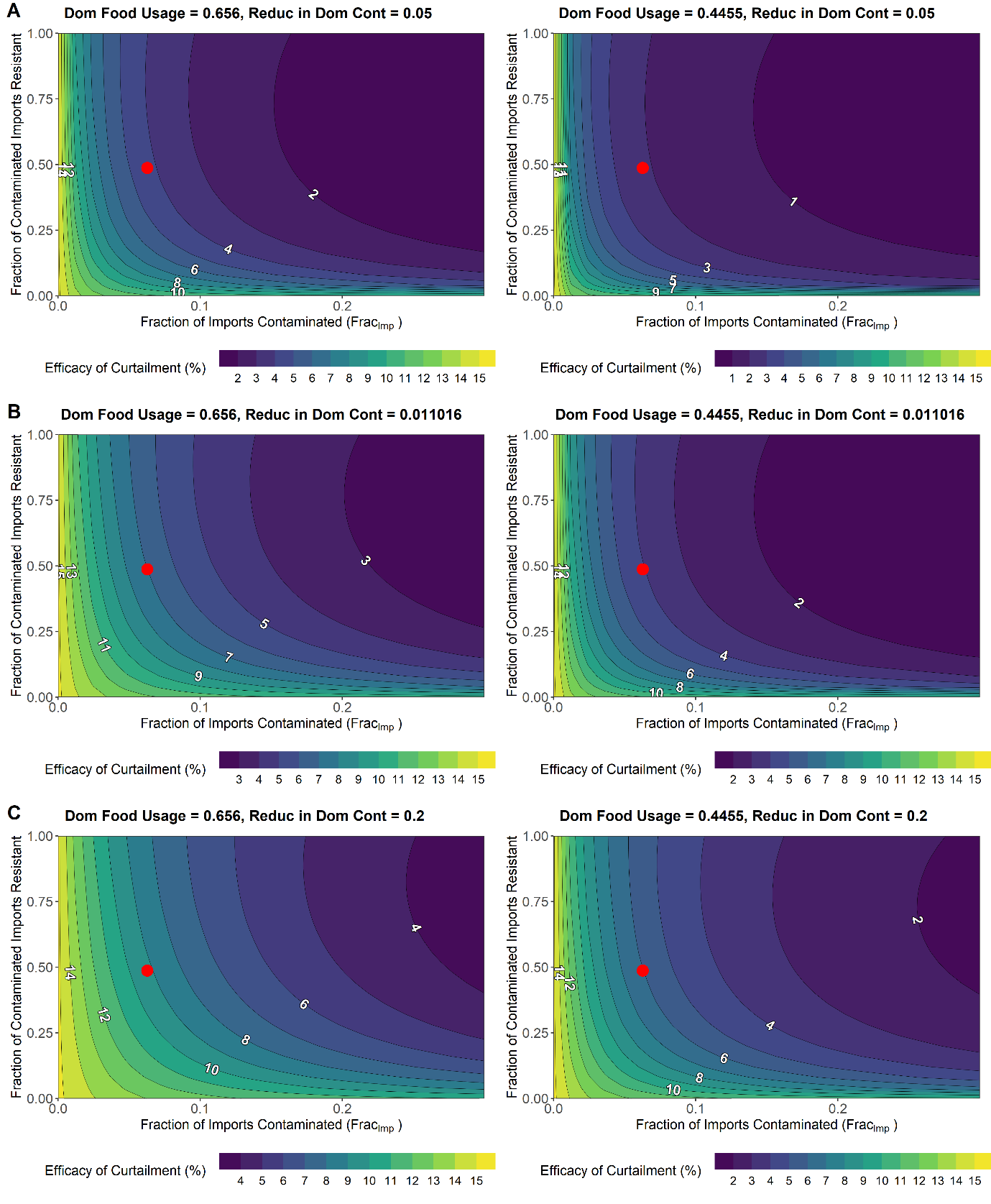
Figure 4. A) **Impact of alterations in livestock antibiotic usage (τ) on the daily incidence of salmonellosis and the proportion of resistant human infection (I\*RHProp). B) Observed and estimated relationship between livestock antibiotic usage data and antimicrobial-resistant salmonellosis in humans.** Solid red lines and ribbons represent model fit resulting from the approximated posterior distribution using ABC-SMC and the corresponding 95% HDI. Country-specific 95% confidence intervals for the observed data (dots) were calculated for each case study using a 1-sample proportion test with continuity correction.

A general sesntivity analysis using LHS-PRCC and eFAST identified the proportion of contaimated imports resistant and the transmission related antibiotic resistance fitness cost as the most important parameters for determing the overall proportion of human resistance. The animal-to-human transmission rate from contaminated carcasses, the proportion of iimports contaminated and the proportion of UK food supply from domestic sources were important for determining the incidence of human salmonellsosis (**SUPPLEMENTARY**). Approximated marginal posterior probability distributions for the fitted model parameters from the ABC-SMC approach and the respective diagnostics can be found in the supplementary material (**SUPPLEMENTARY**).

**Result 3 – effect of altering the ratio of FBD and resistance on the results**

* We have two heatmaps the change in the main outcome measure – but also the change in the other outcome measure – the change in the amount of foodborne disease
* We then have some supplementary material showing the fbd and resistance for the pig case study/

We next identified the effect of import parameters in an uncertainty (or scenario) analysis; the proportion of imported food products contaminated (FracIMP) and the proportion of contaminated imported food products (PropResImp) on the outcome measure on the relative change in human resistance upon the curtailment of domestic livestock antibiotic usage (Efficacy of curtailment – EoC). The parameters were limited to fracimp ϵ [0, 0.3] and propresImp ϵ [0, 1], these values were chosen due to the ranges observed in ECDC datasets (**SUPPLEMENTARY**). The uncertainty analysis also included alterations to the proportion of UK food from doomestiuc sources with baseline and alterantive aprameterisation with psi = 0.454, the proportion of UK food when spercifcially looking at pig imports. We also explored the effect of changing the decrease in proportion from prevalence to contamination in domestic livestock (eta)m exploring a range from baseline, 0.05 (greater clearance) and 0.2 (worst clearance).



**Figure 5. Impact of altering fracimp and propresimp on the efficacy of curtailment for two psi case studies. A) Eta values of 0.05 (better clearance of pathogens). B) Eta values of 0.011 (Baseline). C) Eta values of 0.2 (worse clearance).**

We note that in all analysis increasing the level of contamination and resistance in imported food products has the effect of decreasing the Efgficacy of curtailing, making local interventions less capable of reducing human resistance. Decreases to fracimp and propresimp have the opposite effect, with increases in the efficacy of curtailment (EoC). A related phenomneom can also be observed with decreases to psi with the psi = 0.4455 case study, with equivalence reduictions to fracimp and propresimp resulting in greater reductions to the Efficacy of Curtailment (EoC). Reductions to the eta parameter – resulting a greater level of prevalence being reduced when being transformed to contamination also expands on this phenomenm, wth reductions to fracimp and propresimp, resulting in greater reductions to the efficacy of curtailment (Figure 6A), with the opposite beingf observed when eta is increased to 0.2 (Figure 6C).

This suggests that changes which increase the influence of import on human resistance (increasing contamination (frac imp inceease), imported food usage (psi decrease) and increasing resistance (propres imp decrease), decreasing local contamination (eta increase)) – results in a worse efficacy of curtailment.

* This can likely be attributed to a sort of saturation effect, with the level of attributable resistance from domestic sources decreasing – therefore local interventions will have less of an effect and EoC will decrease

Result 4 – sensitivity analyses LHS-PRCC and eFAST – general case study only

* Supplementary material monotonicity plots

A LHS-PRCC and eFAST sensitivity analysis was next conducted to assess the importance of model parameters on the efficacy of curtailment – with a particular focus on import parameters. We note that the proportion of UK food products from domestic sources () is an important parameter for increasing the efficacy of curtailment (crrelation coef = ) and with the fraction of imports contaminated decreasing the efficacy of curtailment (correlation coeff), under half of the contribution of these parameters () to the variation in the outcome measure can be attributed to second-roder effects including interactions with other parameters.



**Figure 6. Sensitivity analyses for the efficacy of curtailment (EoC) outcome measure. A) Latin hypercube sampling partial rank correlation coefficient test (LHS-PRCC). B) Extended Fourier amplitude sensitivity test (eFAST).** Note that 95% confidence intervals for each correlation coefficient was generated through generating n = 100 bootstrap replicates.

Interestingly the rate of livestock recovery from carriage had a strong effect on reducing the efficacy of curtailment when increased. The proportion of contaminated food products resistant to ampicillin was also found to be important in reducing the efficacy of curtailment. While increasing the proportionate reduction in prevalence to contamination () and therefore increasing the level of contamination on domestic food products, has the effect of increasing the efficacy of curtailment

**Section 2**

To assess the impact of import heterogeneity on the model results we fitted an adapted version of the model with stratified level of importation to the model parameterisation data. The key feature of this model includes a stratification of the homogenous importation transmission pressure into 10 distinct importing countries, FRA, NED, xxx, each with distinct levels of parameterisation required for the level of contamination and resistance on imported food products.

This increased heterogeneity allows for model outcome measures such as the incidence of salmonellosis to attributed to different countries. We note an X-fold increase in the incidence of foodborne disease and a X-fold decrease in human resistance. Approximated marginal posterior probability distributions for the fitted model parameters from the ABC-SMC approach and the respective diagnostics can be found in the supplementary material (**SUPPLEMENTARY**).

Result 6 - Basic Model Output of the effect of withdrawing antibiotic usage on levels of attributable resistance

* Need to alter this figure to have 3 figures here – one for either the unnormalized or the normalised level of resistance (maybe unnormalized levels of resistance would make more sense).
* Supplementary analysis – the effect of changing the level of usage for the levels of resistance

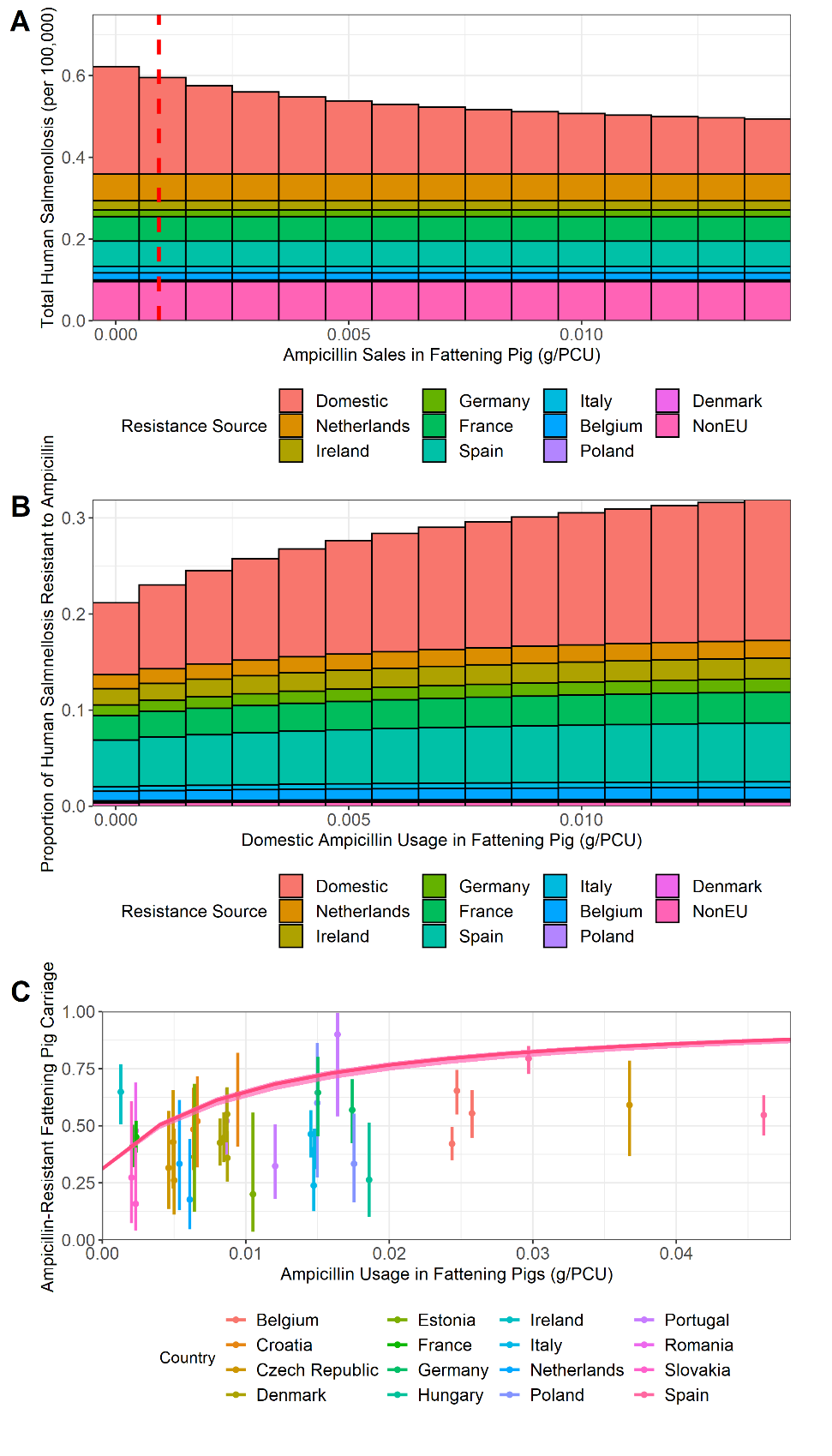


Figure 7. A) **Impact of alterations in livestock antibiotic usage (τ) on the daily incidence of salmonellosis and the proportion of resistant human infection (I\*RHProp). B) Observed and estimated relationship between livestock antibiotic usage data and antimicrobial-resistant salmonellosis in humans.** Solid red lines and ribbons represent model fit resulting from the approximated posterior distribution using ABC-SMC and the corresponding 95% HDI. Country-specific 95% confidence intervals for the observed data (dots) were calculated for each case study using a 1-sample proportion test with continuity correction.

Under baseline model fitting and antibiotic usage – the model predicts that the majority of foodborne disease and resistance are from domestic sources (fbd – 50% and res – 50%), decreasing to lower levels (fbd – 50% and res – 50%) when antibiotic usage is curtailed. As expected the level of attributable fbd and resistance from imported sources do not change when domestic livestock antibiotic usage is curtailed.

Result 6

We next explored the effect of altering the level of UK domestic food supply from domestic sources (psi) on the efficacy of curtailment outcome measure. The relationship between psi and the efficacy of curtailment can be characterised by two areas on the plot, an area where changes to domestic food usage have a greater than proportionate change on the efficacy of curtailment – suggesting that increasing import may more negatively affect the efficacy of curtailment, and an area where changes to domestic food usage has a lower than proportionate change on the efficacy of curtailment.

Chart

Description automatically generated

Figure 8.

We note that the baseline efficacy of curtailment was modelled at 7%, suggesting a relative reduction in resistance from baseline to total curtailment. The baseline relationship between the proportion of UK food products from domestic sources and the efficacy of curtailment sits in this “greater than proportionate” change in the efficacy of curtailment outcome measure – this means that…

To explore the effect of changing the average characteristics of import across importing countries, we explored the effect of changing the average level of import contamiantion , resistance across all importing coutries. We also explored the effect of ranging the extent of reductions to domestic livestock salmonella carraige prevalence on the relationship between the proportion of UK food from domestic sources (ψ) and the efficacy of curtailment (EoC). The average level of contamination was ranged from fracImp ϵ [0, 0.3], in accordance with the range of values observed in ECDC reports.

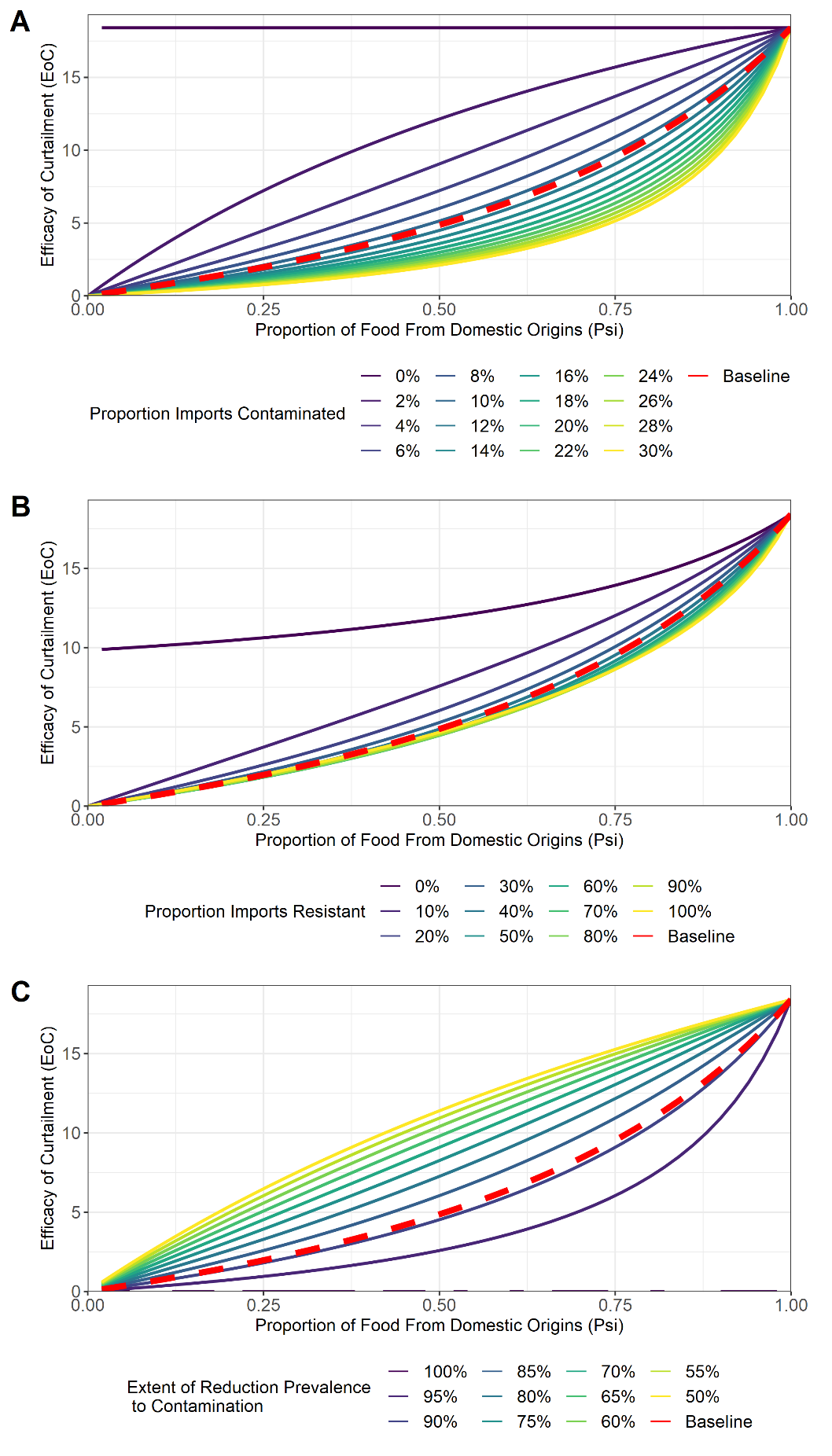


Figure 9.

Decreases in the overall contamination of imported food products to low levels – 0-2%, had the effect of shifting the relationship between the proportion of UK food products from domestic sources and the efficacy of curtailment, to the “green” area where the increase in importation (psi < 0.656) leads to a less than proportionate decrease in the efficacy of curtailment. The opposite phenomenom was observed with increases in the overall level of contamination. Interestingly a “saturation” type effect was also observed, with increases in the average level of contamination above the baseline relationship quickly reaching a similar level to the maximum explored values of contamination.

Changes to the average level of resistance had a similar effect where reductions to the average level of resistance to below 10% shifted the relationship the proportion of UK food products from domestic origins and the efficacy of curtailment to an area where it has a less than proportionate effect on the efficacy of curtailment. Interestingly decreases in the efficacy of the reduction in prevalence to contamination on domestic food products has the effect of shifting the relationship to the area where increases in import have a less than proportionate effect on the efficacy of curtailment.

We next aimed to explore the effect of heterogeneity in the relative contribution across importing countries (ShareImp) on the overall level of import on the efficacy of curtailment. The relative share of import across importing countries were sampled 1000 from two beta distributions, with parameters Beta(alpha = 1, beta = 1) and Beta(alpha = 0.5, beta = 2). These represent two hypotheses about importation – either importing uniformly across different countries in the UKs trade network or importing the vast majority of imported food products from a few select countries. It is important to note that all other parameters are kept to baseline levels when ShareImp. The average effect and the minimum/maximum efficacy of curtailment was identified for each value of theproportion of UK food from domestic sources

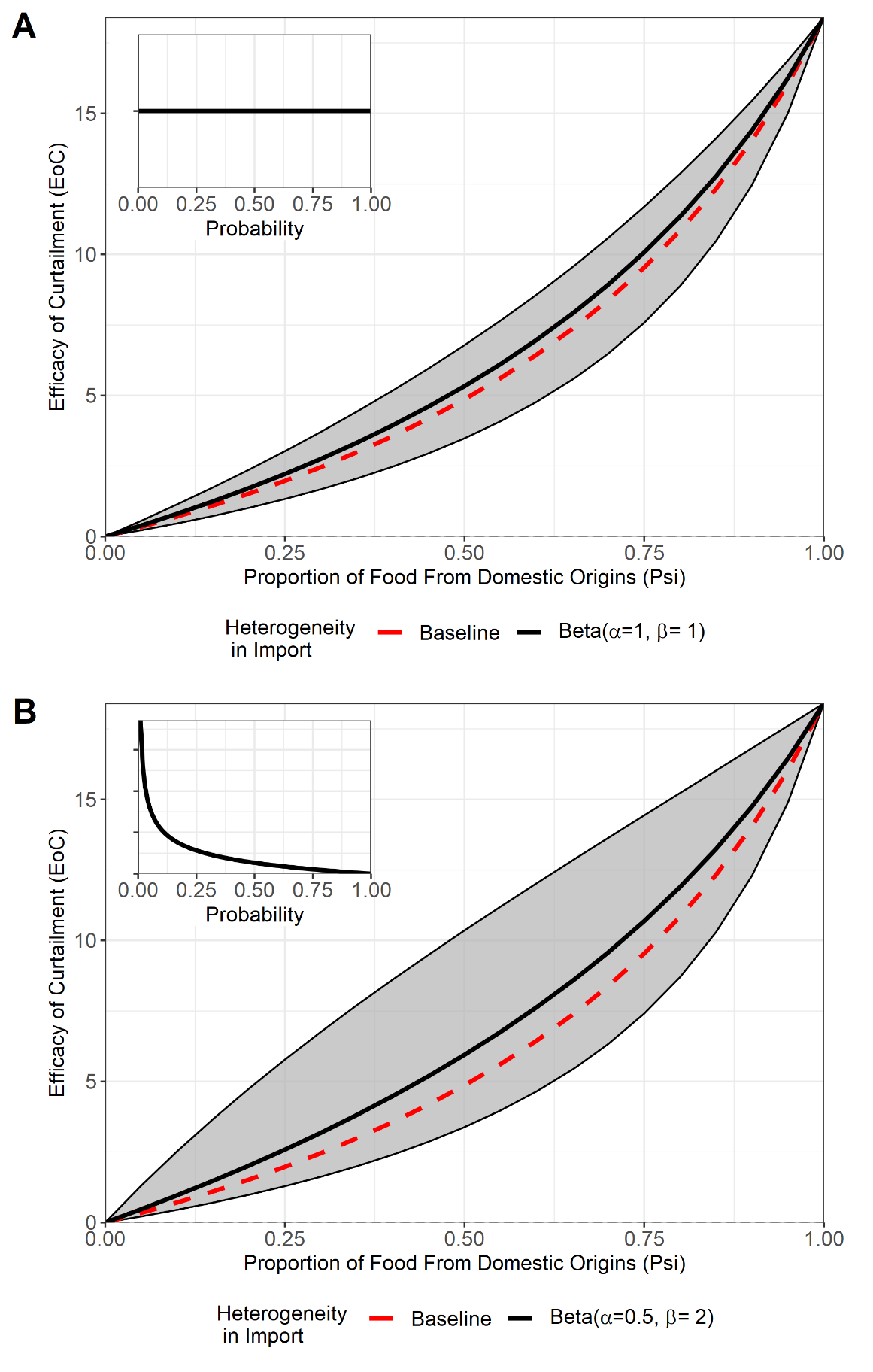


Figure 10.

Sampling from either distribution did not drastically change the baseline relationship between UK food supply from domestic sources and the efficacy of curtailment when observing the average effect. However, we note that a more heterogenous distribution of importing countries will result in a greater level of uncertainty with regards to the effect of the intervention compared to a more unfirom distrinutiom of importing countries.

**DISCUSSION**