Research article

COVID-19 transmission between the community and meat processing plants in Ireland: A retrospective modelling study

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ABSTRACT

Outbreaks of COVID-19 in meat processing plants (MPPs) were recorded globally throughout the pandemic. There was speculation these outbreaks resulted in dissemination of COVID-19 throughout the surrounding county leading to high incidence rates. We aimed to investigate the dynamics of spread between MPPs and their surrounding counties. In this retrospective longitudinal study, data were collected on the number and size of outbreaks in 33 MPPs and county infections in Ireland between March 2020 and May 2021. These data were used to investigate the relationship between outbreaks in MPPs and county infection rates through statistical analysis, and the development of a novel SEIR model. We found an association between the number of MPPs present in a county and county incidence rates, however, incidence rates in the counties did not increase as a consequence of an outbreak in an MPP. The model results indicate that county incidence rates in the weeks prior to an MPP outbreak could reliably predict the size of that outbreak in a plant, $r(49) = 0.62$, $p < 0.0001$, RMSD = 5.6. In Ireland, outbreaks in MPPs were strongly correlated with high levels of infection in the surrounding county, rather than being a driver of infection in the county. The modified SEIR model described here can provide an explanation of the generative process required to cause outbreaks of the size and scale that occur in MPPs.

1. Introduction

COVID-19 outbreaks occurred in workplaces throughout the COVID-19 pandemic. The food-processing industry, which remained open due essential business status, is one of the sectors that proved particularly vulnerable [1] with outbreaks reported in meat processing plants (MPPs) worldwide [2–11]. The transmission of COVID-19 within MPPs due to human and environmental conditions is well documented. Studies have shown extensive morbidity and an increased risk of mortality amongst workers [4,7], and large outbreaks resulted in decisions to restrict movements of residents in surrounding counties (community), interruptions in the food supply chain, and MPP closures [2,4,12].

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A 2020 study from the USA reported that during the first five months of the pandemic, the presence of an MPP in a county was associated with more COVID-19 cases and a higher death rate than in counties without an MPP [13]. Another 2021 USA study investigating the transmission dynamics between MPPs, and the surrounding counties found the per capita COVID-19 cases were higher in counties with an MPP [14]. The role that outbreaks in MPPs had in spreading the infection further in the county is less understood. One of the limitations of studying outbreak data is that it depends on surveillance systems in place. In Ireland, MPPs implemented an active surveillance system with monthly mass testing from August 2020 providing an opportunity to detect outbreaks [15] and study the transmission dynamics between communities and MPPs.

Various models have been used throughout the COVID-19 pandemic to explore aspects of the transmission dynamics of COVID-19 infection. Many of these models were modified to simulate the spread of infection when various control measures such as quarantine or mobility restrictions were implemented or to investigate the dynamics of disease spread at country or continent level [16–21], but not specifically in MPPs. In this study, we examined the relationship between the presence of MPPs in a county and the COVID-19 infection rates reported for the county. We used statistical analysis and a novel extension of a SEIR model to investigate whether an increase in COVID-19 infection rates was observed in the counties with an MPP after a confirmed outbreak of COVID-19 in the MPP. An adapted SEIR model, with S(susceptible), E (exposed), I (infectious) and R (recovered) [16] compartments, was used to investigate smaller scale outbreaks in closed environments. The model explains transmission dynamics by using expressions to describe transmission within the MPP and the binomial distribution to describe the probability of transmission into the MPPs from the county at any given time.

2. Methods

2.1. Data sources

The number of outbreaks, the number of workers, and the geographical location of MPPs in Ireland were obtained from the Department of Agriculture, Food and the Marine (DAFM). During the pandemic, DAFM Official Veterinarians (OVs) gathered outbreak data in the MPPs where they had oversight. For the purposes of this study, we only considered MPPs that had at least 50 workers, as these MPPs were included in a monthly mass testing PCR testing programme initiated in August 2020 and organised by the public health authorities (Supplementary Materials pp 5).

Two separate databases were used to estimate county rates and the size and location of outbreaks in MPPs for the study period from March 2020 to May 2021. The public health authorities in Ireland provide a publicly available database on laboratory confirmed COVID-19 PCR cases [22,23], which has data on a national and local level, and the Central Statistics Office (CSO) Computerised Infectious Disease Reporting (CIDR) database, which includes details of outbreak investigations. Population data were obtained from the CSO [24].

2.2. Investigating the spread of COVID-19 between county and MPP

The spread between MPPs and counties was explored by three methods. First, we correlated the COVID-19 infection rates with the total number of MPPs per county in the country to investigate whether there was an association between presence of MPPs and COVID-19 rates.

Then we used Bland-Altman tests to investigate if the COVID-19 Incidence rates in counties with MPP outbreaks deviated from the national COVID-19 incidence rates pre and post outbreak.

Finally, we used an interrupted time series (ITS) analysis for each of the MPP outbreaks to estimate whether the outbreak had an impact on the COVID-19 rates in the county post-outbreak [25].

2.2.1. Statistical analysis

The per capita COVID-19 incidence rates were calculated for the study period which included the period after mass testing had begun in the MPPs. Then we estimated the correlation between incidence rates and the number of MPPs located in each county using Pearson's product-moment correlation. The geographic spread of the MPPs and the per capita COVID-19 rates during the study period (March 2020–May 2021) was visualised to demonstrate this association.

A Bland-Altman test was conducted to determine whether the county incidence rates were associated with the adjusted national rates at time before the outbreak (60 days before the outbreak) and post-outbreaks (60 days after the outbreak). If an MPP outbreak were to result in significant dissemination of infection throughout the surrounding county, we would expect that to be reflected in a statistically significant difference between the county incidence rate and the national incidence rate after the outbreak had occurred. In the case where an MPP outbreak causes county rates to rise, then higher incidence rates should be observed even after the outbreak has been halted in the MPP. However, if the situation is consistent with the national transmission and spread, then the county incidence rates should be consistent with national incidence rates and no statistically significant difference should be observed.

As the exact duration of the outbreak was unavailable, each outbreak was estimated to be approx. 30 days. This is a conservative estimate of the minimum outbreak length, however, we acknowledge that it could be shorter or longer in duration (several studies have found outbreaks of approximately 4–6 weeks duration in MPPs) [9,10].

The difference between the national and county rates are plotted against the mean of the two incidences. In our situation, we assume that the mean difference is 0, as we would expect little difference between the county and national rates, assuming homogeneous transmission in the community. The limits of agreement are defined as $-1.96s$ and $+1.96s$, with s the observed standard deviation between the two incidences per day.

Interrupted time series (ITS) was modelled for each of the outbreaks using generalised least squares to control for overdispersion of the data. This method allows us to account for autocorrelation via an autoregressive moving average process. The model was used to compare the incidence rate ratio of COVID-19 pre and post outbreak in each county.

The regression equation for this model is given by:

$$Y_t = \beta_0 + \beta_1 T + \beta_2 X_t + \beta_3 Z$$

where Y_t represents the number of COVID-19 cases at time t, T represents the number of days since the start of the pre-outbreak period (60 days prior to the outbreak being notified), X_t is a dummy variable that equates to 0 for the pre-outbreak period and 1 for the post-outbreak period, and Z represents days since the outbreak (equates to 0 for the pre-intervention period). Here, β_0 represents the baseline level of the number of COVID-19 cases at t = 0, β_1 represents the change in the outcome each day pre-outbreak, β_2 represents the change in the level of outcome immediately post-outbreak, and β_3, represents the daily change in COVID-19, post-outbreak.

The plant interventions were implemented when the outbreak was notified. These were not expected to have an effect on the employees already exposed and infected but expected to have an effect on subsequent plant infections, a six day lag time was implemented in the model. This is consistent with the approximate estimate of incubation time for COVID-19 [26–28]. To be eligible for this analysis, the affected counties had to have 60 days of cases prior to the outbreak and 60 days of cases from the date of the intervention (120 days in total).

Fixed effects meta-analysis was then used to compare the pre-outbreak incidence rate of COVID-19 post-intervention with the post-outbreak incidence for each outbreak. This analysis would determine whether the outbreak had any effect on the county infection rates, subsequent to the outbreak.
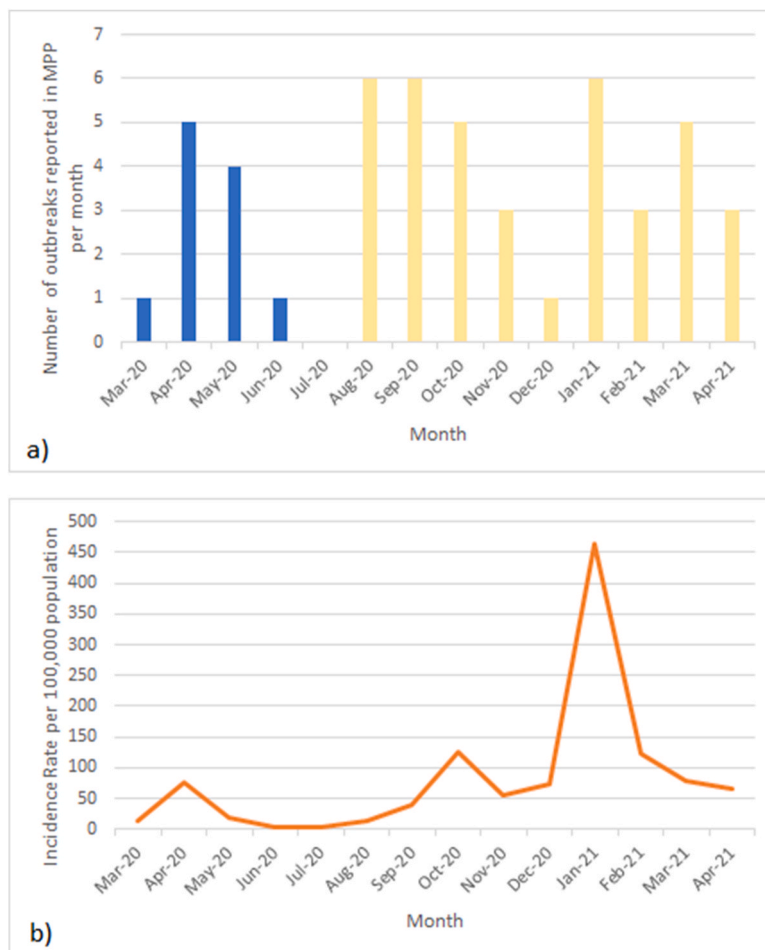

Fig. 1. (a). The number of COVID-19 outbreaks reported in MPPs for the given month (bar chart). The blue bars represent spontaneous outbreaks, and the yellow bars represent outbreaks that occurred during the screening period of MPP workers by the public health authorities. Fig. 1(b) The orange line represents the average monthly (daily reported incidence rates were averaged for each month) national incidence rate per 100,000 population in Ireland Mar 2020 to May 2021. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2.2. Sensitivity analysis

To test robustness of the six day lagged analysis, using two additional sensitivity analyses for a zero day lag and a 12 day lagged time frame.

2.3. Epidemiological modelling

To model the role of county infection transmission in MPP outbreaks, we developed a model using a standard SEIR disease transmission model and the binomial probability distribution (Supplementary Materials pp 11–14). This extended SEIR model (SEIR$_w$) describes how intermittent introduction of the virus into MPPs (i.e, by workers who have acquired infection in the county entering the MPP), sustained outbreaks in Ireland between March 2020 and May 2021 in 33 MPPs. This period was marked by a number of MPP outbreaks and fluctuations in COVID-19 incidence among the general populace.

The transmission of COVID-19 within the workplace was modelled using the standard SEIR expressions and the employees were assigned to one of the Susceptible-Exposed-Infected-Recovered model compartments. The movement of the employees between the compartments were governed by the transmission, incubation, and recovery rates. For the model, we assume a workplace with N employees, take β (*transmission*), α (*incubation*) and γ (*recovery*) *rates*, for the disease in a workplace (so that the reproductive number is $R = \beta\gamma$) and take S_t (*susceptible*), E_t (*exposed*), and I_t (*infectious*) at a given time, t (we do not report estimates for R_t, the number of recovered individuals at a given time). In addition, we assume that new infections may periodically enter from the surrounding county. To calculate the probability of infections entering from the county and producing new infections in the MPP, we created a list of infection probability on any given day for the county using the incidence rate (subject to some lag). We assume that contact is intermittent. On days where no contact between the county and the MPP occurs, the probability of infection is set to 0. On days where county-MPP contact occurs, the probability of infection is derived from the infection probability list.

To estimate the number of infections in the workplace at the defined "end time", we use the day, the county probability list, and estimated values for S_t, E_t, and I_t as input for the model. The model then works recursively to produce a discrete probability distribution for the estimated number of exposed and infected individuals at t_{end}.

On days where no community contact takes place, the number of susceptible, exposed, and infected individuals in the MPP update according to the standard SEIR expressions. On days where there was some probability of community infection, then the number of workplace infections are produced based on the SEIR expressions, along with new infections which are produced by the community contact.

Statistical analysis and modelling was carried out in RStudio using R version 4·2·2 [29], using the packages data.table, lubridate, ggplot2, nlme for general analysis and graphing and the packages sf, dplyr, ggplot2, and viridis for the geographical plots.
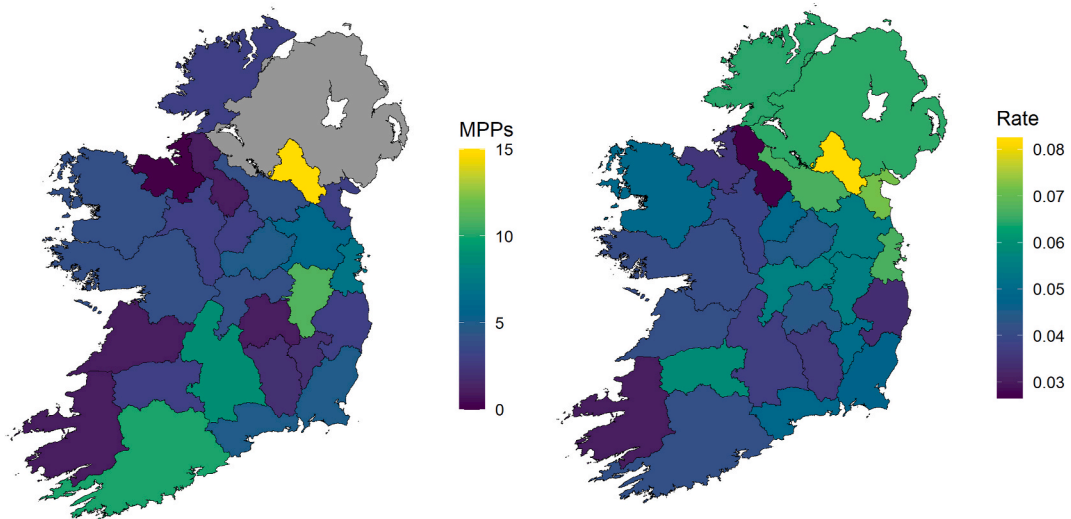

Fig. 2. a. (left) shows the total MPPs per county in Republic of Ireland. The darker colours indicate a lower number and brighter colours indicate a higher number. MPPs in Northern Ireland (shown in grey) are not included here. (b) shows the per capita COVID rates for each county in the Republic of Ireland and an average per capita rate for Northern Ireland for the study period. Per capita rates were calculated using the cases per county and the county population. Lower per capita rates are shown in darker colours, while higher rates are shown in brighter colours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results

3.1. Descriptive analysis of COVID-19 outbreaks in MPPs and county incidence rates

OVs provided data on the occurrence of 49 COVID-19 outbreaks in 33 MPPs during the 14-month period between Mar 2020–May 2021 (Supplementary Materials pp 6).

The number of outbreaks reported by MPPs per month (Fig. 1a) was compared to the national incidence rate (Fig. 1b). During the early months of the pandemic when the national incidence rate was high, more outbreaks were also reported in MPPs. In August 2020, Epidemiological week 32 marked the beginning of the second wave of COVID-19 infection in Ireland when the national incidence rate started to increase. There was also an increase in confirmed MPP outbreaks coinciding with the commencement of an active surveillance programme by the public health authorities whereby MPP workers were targeted for PCR testing at least every four weeks or more frequently. This was based on a risk assessment of the MPP by the public health authorities, or where two or more cases confirmed positive from the surveillance testing or following notification of an outbreak by the MPP to the public health authorities.
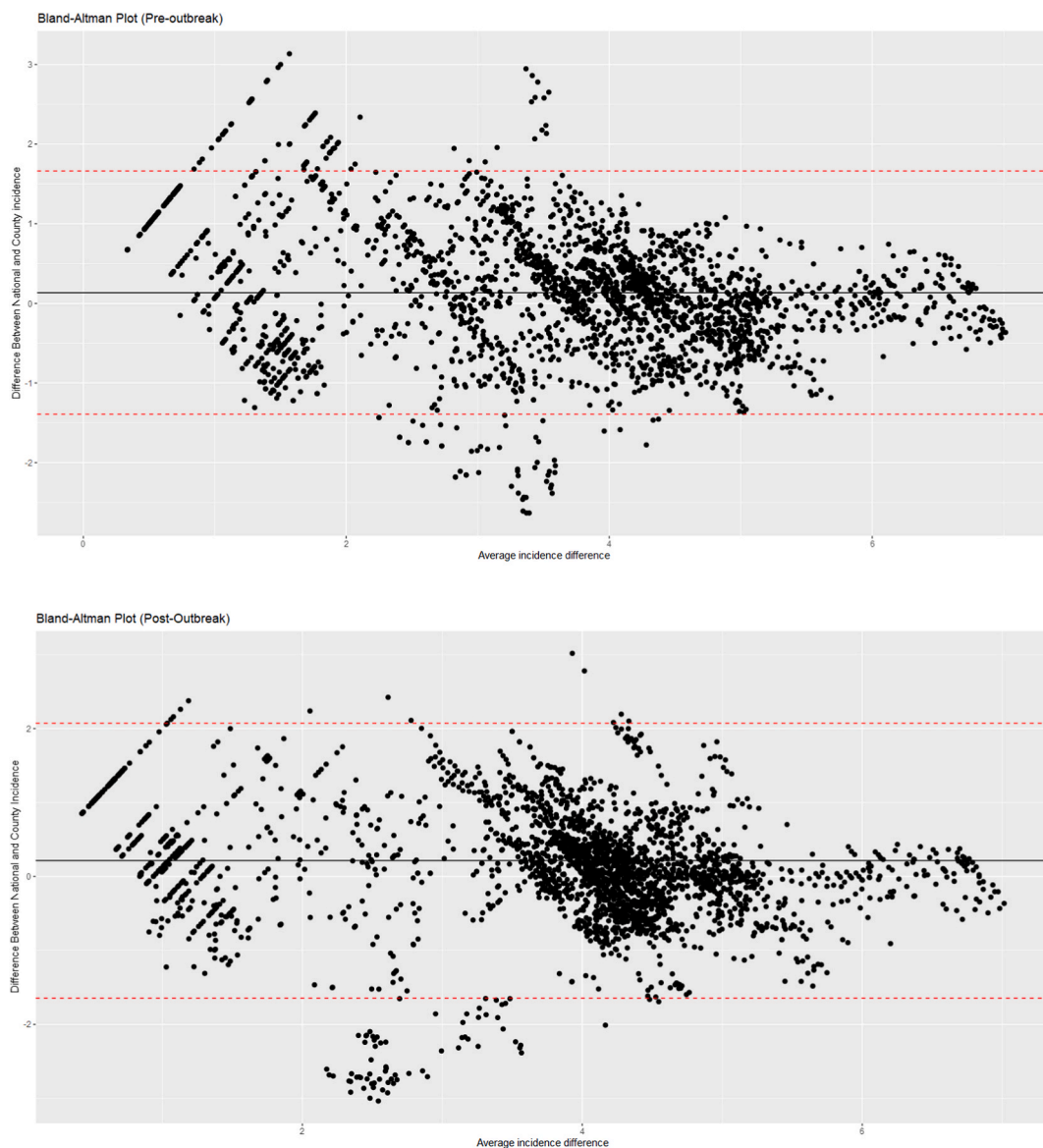

Fig. 3. (a). The upper Bland-Altman plot shows the agreement between the national and county rates (log-transformed) before MPP outbreaks occurred. The solid black line indicates the log-transformed mean difference, and the dashed lines indicate the upper and lower limits of agreement. Fig. 3(b): The lower Bland-Altman plot shows the agreement between the national and county rates (log-transformed) after MPP outbreaks occurred. The solid black line indicates the log-transformed mean difference and the dashed lines indicate the upper and lower limits of agreement.

3.2. Statistical analysis of the relationship between the number of MPPs and the number of COVID-19 cases per county

To determine whether there was an association between the number of MPPs in a county and per capita COVID-19 cases, we used the data to correlate those measures for the entire study period and for the period after mass testing in plants had begun. We found a moderate positive correlation for both the entire study period, $r(24) = 0.49$, $p < 0.01$, and the period from August 2020 during which serial PCR testing was being undertaken in MPPs, $r(24) = 0.46$, $p < 0.01$. Fig. 2 illustrates this moderate relationship between the number of MPPs (Fig. 2a) and per capita COVID-19 cases in each county (Fig. 2b).

3.3. Statistical analysis of the COVID-19 outbreaks in MPPs and county incidence rates

To investigate whether MPP outbreaks were producing increased county incidence rates, we looked for deviations between the county and national mean incidence rates pre and post outbreak.

Shapiro-Wilks test was used to determine whether the difference between the county and adjusted national incidence rate were normally distributed. As they were not (W = 0.76222, p < 2.2e-16), the data were log transformed.

For the pre-outbreak scenario, the mean difference is 0.13 and the 95 % limits of agreement is −1.39 and 1.66 (see Fig. 3a). Log-transformed variables can be difficult to interpret, so we transform the limits of agreement back by using the antilogs. The mean difference is −2.46 and the upper and lower limits of agreement are 129.15 and −126.95. This suggests, on average, that the mean difference in incidence rate between the national and county incidence before an outbreak is small.

For the post-outbreak incidence, a log mean difference of 0.07 was observed, with upper and lower limits of agreement 1.58 and −1.37, respectively (see Fig. 3b). We transform the limits of agreement back by using the antilogs. The mean difference is −5.31 and the upper and lower limits of agreement are 119.82 and −117.61. This suggests, on average, that the mean difference in incidence rate between the national and county incidence after an outbreak is also small.

3.4. Time series analysis

Forty-one of the outbreaks were eligible for the ITS analysis. For the six day lagged analysis, the pooled estimates showed no significant step change immediately post-outbreak (pooled incidence rate ratio (IRR) = 2.26, 95 % CI = 0.82–6.22, p = 0.11). Additionally, no significant change was observed in the daily Covid-19 rates, post-outbreak (pooled IRR = 1.01, 95 % CI = 0.97–1.04, p = 0.71).

3.5. Sensitivity analysis

As with the primary analysis, the sensitivity analysis showed no significant step change in COVID-19 incidence rates immediately post-outbreak for either a zero-day lag (pooled IRR = 0.86 95 % CI = 0.31–2.34, p = 0.76) or for a 12-day lag (pooled IRR = 0.2, 95 % CI = 0.03–1.53, p = 0.12).

Daily change in post-outbreak COVID-19 rates showed no significant difference for the zero lag analysis (pooled IRR = 0.99, 95 % CI = 0.97–1.03, p = 0.99). However, a significant change in daily COVID-19 rates was observed from day 12 post-outbreak onwards (pooled IRR = 1.04, 95 % CI = 1.00–1.08, t = 2.04, p = 0.04).

4. Testing SEIR_w model predictions

For initial analysis we assumed a reproductive number of $R_0 = 3$, incubation time of 6 and recovery time of 6 (values consistent with the ranges for estimates reported in previous research) [30,31], giving $\alpha = 1/6$, $\gamma = 1/6$ and $\beta = R_0\gamma = 1/2$. The initial call to the SEIR_w model was $t = 1$, $S = 0$, $E = 0$, and $I = 0$, respectively. The SEIR_w model was used to predict the size of the outbreak which
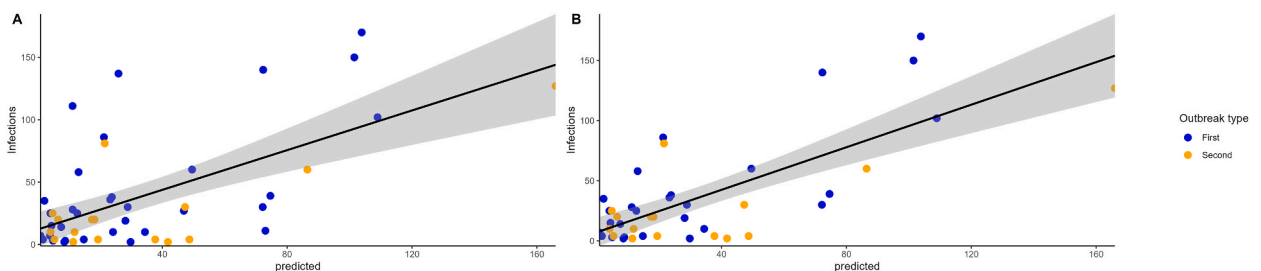

Fig. 4. (a) Scatterplot of observed and predicted COVID-19 outbreak size for MPP in Ireland during 2020 and 2021. First outbreaks in each plant are represented by blue circles, and second outbreaks where they occurred by orange circles. The line represents the linear regression of best fit between observed and predicted values, and the shaded area the standard error of that fit. (b) The scatterplot above shows the observed and predicted outbreak size for the outbreaks after May 1st, 2020 in Ireland. The diagonal line is the linear regression best fit line and the shaded area shows the standard error in fit.

occurred at each MPP, and this was compared with the actual (observed) size of the outbreak at each location.

We ran this model with a range of values of x (*starting week before outbreak*) and L (*lag*) when fitting the model to data and assessed degree of fit in terms of the correlation between observed and predicted outbreak size, and in terms of the average difference (Root Mean Squared Deviation) between observed and predicted size. For the first outbreak, the best fit arises with values $x_{first} = 1, L_{first} = 3$ and for the second outbreak, the best fit values were $x_{second} = 3, L_{second} = 0$; with these parameter values the correlation between observed and predicted outbreak numbers overall was $r = 0 \cdot 62$ ($p < 0.0001, RMSD = 5 \cdot 6$; Fig. 4a). Analysing further, we found that prediction accuracy was notably higher for second outbreaks ($r = 0 \cdot 77, RMSD = 7 \cdot 6$) than for first outbreaks ($r = 0 \cdot 61, RMSD = 11 \cdot 7$). It seems likely that this difference in accuracy arises because reported county incidence rates were weaker reflections of the true incidence rate in the county early in the pandemic. We hypothesised that the difference in prediction accuracy may be due to inaccurate reporting of case numbers at the outset of the pandemic for reasons such as infrastructure for testing and reporting may not be fully operational. We repeated the computations for outbreaks after May 1st, 2020, and found an overall improvement in model prediction, $r = 0.74$ ($p < 0 \cdot 0001$, RMSD = 3.27, Fig. 4b). No second outbreak occurred prior to May 1st, so no change was observed for 2nd outbreaks.

4.1. Reproduction numbers

Where the above analysis assumes a constant reproduction number R, we also developed a modified version of this algorithm where first outbreaks were subject to some value R_{first} and second outbreaks some different value R_{second}. Since second outbreaks are very likely to arise in the context of protective workplace measures (that is, lower workplace R numbers), we would expect model fit to improve with higher values for R_{first} than R_{second}. Running the model just as above but $R_{first} > R_{second}$ produced a higher overall correlation between predicted and observed outbreak numbers while cases where $R_{first} < R_{second}$ produced an overall lower correlation value (Table 1). Hence, model fit is improved by giving more realistic values for R. This supports the use of the $SEIR_W$ model to predict the risk of a large outbreak occurring in the workplace.

5. Discussion

To the best of the authors' knowledge, this is the first study in the literature where data have been collected and analysed on a national scale for outbreaks that occurred in MPPs over an extended period. This longitudinal study examined the relationship between COVID-19 outbreaks in MPPs and incidence rates in surrounding counties. The results indicate that outbreaks were unlikely to result in higher county incidence rates in the long-term as the county incidence rates were typically consistent with each other pre- and post-outbreak and consistent with the adjusted national incidence rate post-outbreak. We tested a novel method for modelling the dynamics of spread between MPPs and their surrounding counties. Using a modified SEIR-type model, we tested the hypothesis that MPP outbreaks could be predicted by county incidence rates. The results demonstrated that the direction of spread of infection is more likely to be from the wider county into MPPs, rather than from MPP outbreaks into surrounding counties.

During the study period of March 2020 to May 2021, the Irish public health authorities were notified of 722 non-healthcare workplace-related outbreaks, of which 106 (15 %) were reported in MPPs [22,23]. These data demonstrate there is high risk of outbreaks occurring Irish MPPs in line with the frequency of MPP outbreaks reported globally [1,32]. The MPP outbreaks accounted for 46 % of the laboratory confirmed cases in these non-healthcare workplace-related outbreaks. However, MPP workers were very likely to have been over-represented in these case numbers due to serial PCR testing implemented exclusively for MPP workers. The study results show that outbreaks occurred throughout the country and in MPPs with various sizes of workforce. Although large outbreaks received increased media attention and were labelled as a significant risk to the population at large, this narrative does not appear to be a true reflection of outbreaks that occur in Irish MPPs generally. Of the 49 outbreaks we have data for, 37 outbreaks (76 %) had between 2 and 49 cases and 6 outbreaks (12 %) had over 100 cases.

In determining the relationship between MPP COVID-19 outbreaks and county incidence rates, our statistical analysis shows that MPPs had little measurable impact on incidence rates in the surrounding county. Instead, our model predictions suggest that previous county incidence rates have a great impact on the size of MPP outbreaks. This is in contrast to other studies in the USA, where it was reported the per capita COVID-19 cases increased post-outbreak in counties with MPP establishments [14] and there was a strong positive relationship between large MPP that process over 10 million pounds per month and local county transmission of COVID-19

Table 1
Modified Reproductive numbers. The model assumes that the reproduction number was constant for both the first and second outbreaks. As this is an unrealistic assumption, we tested the model with different values for R for the first and second outbreaks. We found that prediction improved where $R_{first} > R_{second}$. Notably, lower correlation values are observed where the reproductive number is higher for the second outbreak than the first. The overall correlation values and RMSD between observed and predicted numbers are shown below.

R_{first}	R_{second}	r	RMSD
3	3	0·62	5·6
3·5	2·5	0·66	5·1
2·5	3·5	0·49	12·2

[13]. However, compared to Ireland, the USA has a very different meat industry model which is based on large enterprises. For example, the largest pig MPP in the USA has 5000 employees and is based in Bladen County, NC (pop: 29,000). Assuming that most of the employees are resident in that county, then nearly 20 % of the county residents could be working in this MPP. In their study, Taylor et al. also found no significant relationship between small/medium MPPs and county transmission [13]. MPPs in Ireland operate on a much smaller scale with an average sized MPP employing about 300 workers [33] which other studies suggested was a possible mitigation strategy to prevent large outbreaks in possible future pandemics [13,14].

In the study period while MPP outbreaks were ongoing, there were statistically higher county infection rates than during the pre- and post-outbreak periods. However, these outbreak periods coincide with times where national incidence rates were also high, indicating that MPP outbreaks were likely to occur during periods of high infections in the county and nationally. This aligns with the model data from a 2021 study regarding pork processing plants, that outbreaks could be initiated and propagated by county transmission into the MPP rather than the reverse [34]. Similar to the findings of Saitone et al. [14], more outbreaks were reported in MPPs in the early part of the pandemic, and first outbreaks in MPPs were more likely to occur earlier in the pandemic. This could be attributed to many factors including the suitable environment for airborne spread, along with the lack of appropriate mitigation measures being implemented in MPPs before transmission pathways and risk factors for transmission were established.

Previous studies that investigated within-plant transmission of COVID-19 showed that rapid antigen or PCR testing are the most effective strategies which reduce the introduction of COVID-19 into an MPP [35]. As forementioned, in Ireland, serial PCR testing was implemented in MPPs in August 2020. MPPs also implemented risk mitigation guidelines targeted specifically for MPP settings. These guidelines, provided by the public health authorities in May 2020, consisted of 80 different strategies incorporating physical, social, and environmental changes in MPPs to reduce the possibility of airborne, droplet, and fomite transmission. Moreover, our previous research has shown that MPPs started implementing risk reduction measures even before May 2020 [10] and these measures were maintained throughout the pandemic. Our data show that in counties that had MPP outbreaks, county level incidence was strongly related to national incidence rates. County level incidence in the preceding month was a good predictor of outbreak size. We found no evidence to suggest that outbreak size was related to post outbreak county level incidence rates. In Ireland, outbreaks in MPPs were strongly correlated with high levels of infection in the surrounding county, and there is no evidence to suggest that the MPP outbreaks were a driver of subsequent infection in the county. Implementing effective risk mitigation measures that prevent infection from entering or reducing transmission within the MPP is key to preventing large outbreaks [14,35,36].

In August 2020, the decision to close non-essential businesses including restaurants, cinemas and gyms, and restrict resident travel outside of the county for three counties in Ireland was influenced by MPP outbreaks occurring in those counties [37–39]. Several studies showed that population-level COVID-19 restrictions come with significant social and economic cost [40,41]; and in future pandemics, evidence-based decision making on the use of difficult population-level non-pharmaceutical interventions is needed [42]. Understanding, that despite the predominant narrative, MPP outbreaks were most likely as a consequent to high levels of infection in the surrounding county. This demonstrates the importance of retrospective evaluation in providing evidence for dealing with similar crises in the future.

5.1. Study limitations

An important caveat for interpreting our study is that the dataset was not as detailed or extensive as hoped, by virtue of both gaps and lack of detail in the CSO data and data from MPPs. As the dataset only included MPPs with at least 50 workers, the results are not generalisable to smaller MPPs. Furthermore, OVs who provided responses were reporting historic data provided by MPP management. Improved reporting and surveillance capabilities in MPPs would allow for refined data collection. Data collected from the OVs was sometimes difficult to cross-reference with CSO records and may have lacked specificity.

In particular, data from early in the pandemic was difficult to identify in the outbreak database. The CSO database only included cases identified by mass testing in the plant, whilst the OV reports may include cases that were identified prior to or post mass-testing by other means.

5.2. Direction for further research

This research highlights the importance of detailed surveillance data in understanding infection spread. While the available data allowed us to investigate infection spread in MPPs, as a whole, and throughout the county, some work areas in the plants, such a boning halls, have been highlighted as particularly vulnerable to infection spread [6,10,43]. As reviewed by Hosseini et al. (2022) [35], migrant and ethnic minority workers are more likely to be engaged in essential work and be overrepresented in certain occupations. Being placed in environments that increase the risk of transmission, such as areas with poor ventilation or lack of room for effective physical distancing suggest a disproportionate risk for COVID-19 infection. Understanding the areas within the MPP where positive COVID-19 cases are recorded enable MPPs to implement effective risk mitigation strategies where they are most needed and is essential to future proofing the MPP industry and protect its workers.

This research also highlights the potential of using a model to understand the generative process that results in outbreaks in MPPs. This retrospective hypothesis testing of the epidemiology of infectious diseases, could be an integral component of risk mitigation strategies going forward that can be implemented to decrease the risk of COVID-19, or other airborne pathogens, from entering MPPs and generating large outbreaks.

Ethical statement

This study was reviewed and approved by University College Dublin Human Research Ethics Committee, with the approval number: LS-E-20-196.

Data availability

The data supporting the study findings are available on request from the corresponding author. A complete R script and datafile which implements the extended SEIR model, carries out the statistical analysis, and generates the figures reported here is available online at https://osf.io/5uxrv/

CRediT authorship contribution statement

Rita Howe: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Charlene Grice:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Fintan Costello:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Conceptualization. **Vicky Downey:** Writing – review & editing, Methodology, Conceptualization. **Donal Sammin:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Carla Perrotta:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Grace Mulcahy:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Nicola Walshe:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e30919.

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