

Risk of COVID-19 Introduction into the Scottish Hebrides and Strategies for Control

Anne-Sophie Ruget

Roslin Institute

Christopher J. Banks

Roslin Institute

Jessica Enright

School of Computing Science, University of Glasgow

Rowland R. Kao (✉ rowland.kao@ed.ac.uk)

Roslin Institute

Research Article

Keywords: mobility data, COVID-19 introduction, stochastic simulations, seasonality, Hebrides

Posted Date: August 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-721590/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

RESEARCH

Risk of COVID-19 introduction into the Scottish Hebrides and strategies for control

Anne-Sophie Ruget¹, Christopher J. Banks¹, Jessica Enright² and Rowland R. Kao^{1,3*}

*Correspondence:

rowland.kao@ed.ac.uk

¹The Roslin Institute, University of Edinburgh, Easter Bush Campus, Edinburgh, Scotland

³Royal (Dick) School of Veterinary Studies, University of Edinburgh, Edinburgh, Scotland

Full list of author information is available at the end of the article

†Equal contributor

Abstract

Background In the context of an outbreak the natural boundaries of islands can allow for control of movements between populations. We estimate the risk of introduction of COVID-19 to each of the Hebridean islands situated off the west coast of mainland Scotland due to individual movements, and explore control strategies to mitigate this risk.

Methods We use a combination of real human mobility data and census data to generate seasonally varying patterns of human movements amongst the Hebrides and from elsewhere. We consider three distinct periods: each of summer and winter 2019, illustrating a year prior to the pandemic, and summer 2020 illustrating a “pandemic summer”. Movements during these periods serve as input to simulate COVID-19 transmission from the mainland to the archipelago in a stochastic meta-population model allowing us to explore the impact of seasonal variations on the risk of introduction and the effectiveness of non-pharmaceutical interventions.

Results Despite strong seasonality in movement patterns, partly driven by tourism, for islands closely connected to the mainland there is evidence of substantial risk of disease introduction even over winter.

In summer, when the risk is the highest, some islands can delay the introduction of COVID-19 by over six weeks, i.e. beyond the summer holiday period, through a 70% reduction of movements.

Conclusion A high introduction risk in winter will be of particular concern if COVID-19 becomes a seasonal respiratory infection affecting temperate areas in winter concomitantly with other seasonal infections such as flu.

For some islands, control of movements in peak summer tourist season has the potential for delaying the introduction risk beyond the summer holiday period, i.e. beyond a period of high mobility of people, potentially inducing a risk for rapid spread. Such measures would be particularly relevant in the occurrence of a variant escaping the vaccine given the current progress of the vaccine roll-out. However, such restrictions must be balanced against indirect negative economic impacts that might result.

Keywords: mobility data; COVID-19 introduction; stochastic simulations; seasonality; Hebrides

Background

Numerous viruses causing respiratory diseases that have been responsible for large epidemics in the past were identified as a pandemic threat (MERS, SARS, Influenza.... [Reperant and Osterhaus \(2017\)](#)). In December 2019, the first cases of pneumonia due to the new virus SARS-Cov-2, now called COVID-19, were identified. The virus rapidly spread to Europe including Scotland, where the first death

was recorded on March 16th 2020 ([National Records of Scotland, 2020a](#)). Following the introduction and spread of the virus, the first lockdown was declared on March 23rd 2020. Since then the virus has continuously spread within the (United Kingdom) UK, at various levels. The first lockdown proved effective at reducing the circulation to a very low level ([National Records of Scotland, 2020b](#)). The rise in cases following the lifting of the restrictions in July 2020 was mostly due to importation ([Lycett et al., 2021](#)), showing that within the course of the epidemic, re-introduction of viruses between communities may play an important role and controlling these re-introductions may be key to reducing the spread and therefore the impact.

The geographical context of islands and their natural boundaries might have an impact on how the disease spreads compared to the mainland. In addition, in the context of a respiratory disease spread by movement of people, the natural boundaries of islands make measurement of the flow of people entering the islands, or circulating between the islands easier. It also potentially allows for a better control of flow between populations. With regards to COVID-19, New Zealand illustrated an example of how to take advantage of the geographic isolation to locally eliminate a pathogen ([Cousins, 2020](#)).

Modelling approaches can help us better understand the importation risk taking into account movement pattern and disease process. Such methods have been used in various contexts such as the Ebola epidemic in 2014 ([Poletto et al., 2014](#)), and for influenza epidemics ([Mateus et al., 2014](#)), and have shown that movement restrictions can only delay the introduction but not prevent it, unless movements are suppressed. Whilst facing the spread of a new virus, every week allows for a better understanding of the disease dynamic, for potentially better treatments and interventions, or even a larger vaccine coverage of the population. In such a situation it might be useful to delay the introduction, even for a short period of time, as the breadth of knowledge and means are rapidly growing.

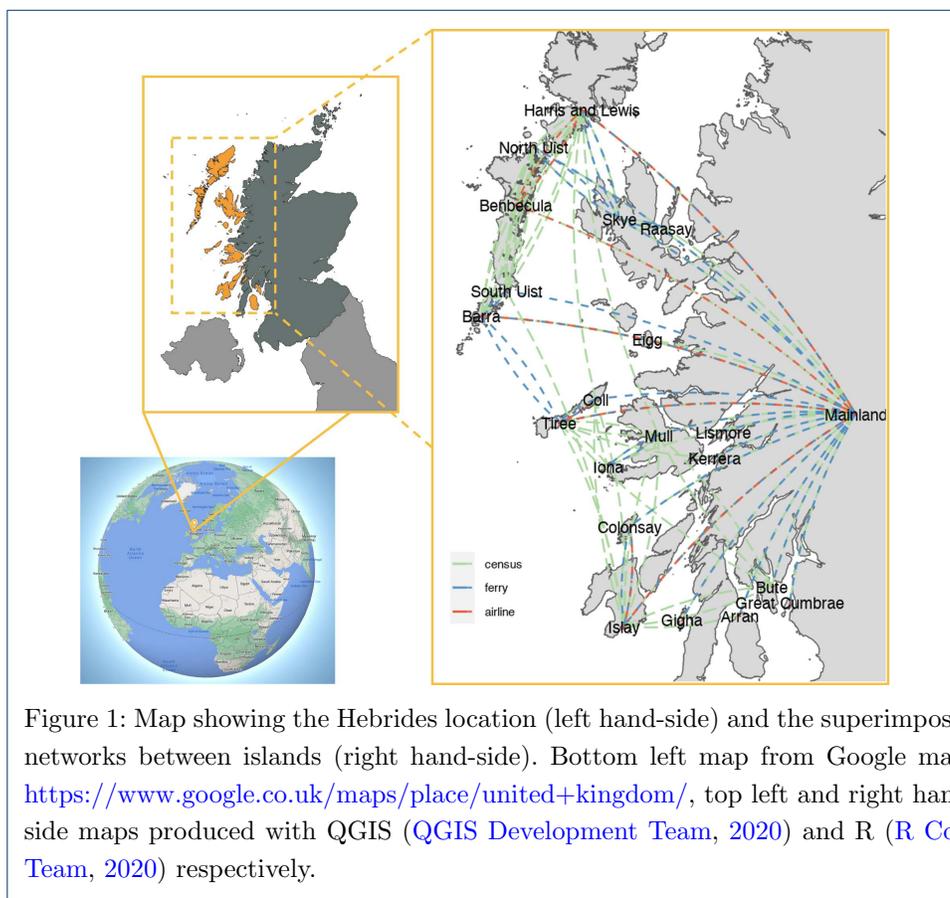
In Scotland, most of the cases and deaths due to COVID-19 have occurred in the most densely populated part of the country, called the central belt. The Scottish isles have been less affected by COVID-19, although multiple introductions of the virus have occurred. Movements between Scotland mainland and the isles experience high seasonal variations due to tourism and seasonal workers. Our objective was to assess the risk of introducing a respiratory disease such as COVID-19 in the Hebrides, an archipelago off the west coast of mainland Scotland according to flow of people. We estimated the short-term risk of introduction in summer vs. winter prior to the pandemic situation using data from 2019, and highlighted the change of risk between seasons. We then considered the summer 2020 illustrating a peak season period within the pandemic and estimated the risk of introduction as well as the impact of movement restrictions on this risk. Finally we explored control scenarios based on movement restrictions and Non-Pharmaceutical Interventions (NPIs) inducing a mitigation of contacts between individuals and therefore disease transmission.

Methods

Data and model

Data

To be able to reproduce the pattern of movement relevant to disease spread from the mainland to the islands we combined publicly available data with data provided by transport companies. The Census Flow Data is an official statistics and corresponds to the number of people moving between declared home locations and workplace locations. This data is available online for academic institutions ([UK data service, 2011](#)). The Civil Aviation Authority (CAA) publishes monthly reports providing number of passengers between airport ([Civil Aviation Authority, 2020](#)). Skye is the single island in our study having a road link to the mainland. Transport Scotland shared with us statistics on direct vehicle movements into the Islands system via Skye bridge traffic, providing a number of cars in each direction per hour between January 2019 and December 2020. Finally the ferry company (Caledonian MacBrayne, or "Calmac") operating between 19 islands of the Hebrides provided number of passengers per ferry on scheduled routes between January 2019 and October 2020.



We used these data to construct a combined network at the output area (OA) level. The output area is an administrative unit containing approximately 50 inhabitants. Fig. 1 shows the location of Scotland and the Hebrides, as well as an aggregation of the three networks at the island level superimposed with a map.

Since we considered a combination of data collected in real time and data from the 2011 census, we expected some movements to appear in more than one of the datasets. To avoid overestimating movement volumes, we calculated the edge weights, considering only the largest volume between the census data or the ferry and bridge data. We assumed that there is no overlap between airline data and census data, as individuals are unlikely to commute regularly by air.

Large seasonal variation in volumes were clear in 2019, as well as large changes in volume due to restrictions in 2020 (see Fig. 2). When we constructed our combined network, we therefore considered three sets of weights for the edges compatible with three periods: summer 2019, winter 2019, and summer 2020. These three periods reflect different situations: summer and winter 2019 illustrate the seasonal variation in a typical year, whereas summer 2020 represents a holiday period during the pandemic with no movement restrictions in Scotland (ISSN International Centre, 2020).

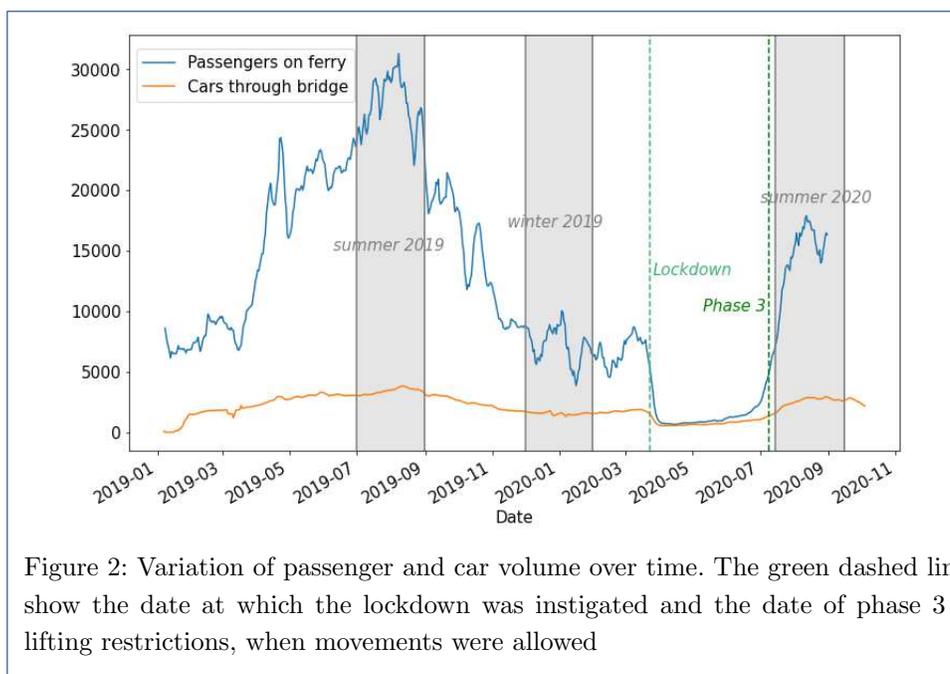


Figure 2: Variation of passenger and car volume over time. The green dashed lines show the date at which the lockdown was instigated and the date of phase 3 of lifting restrictions, when movements were allowed

While there may be some overlap, each dataset contained differing information: the ferry data contained a number of passengers from port to port per date and time, the airline data contained a monthly volume between pairs of airports, the Skye bridge data provides a number of cars per hour of the day from January 2019 to December 2020. To homogenise the data and construct between-OA movements of individuals, we processed the data as described below:

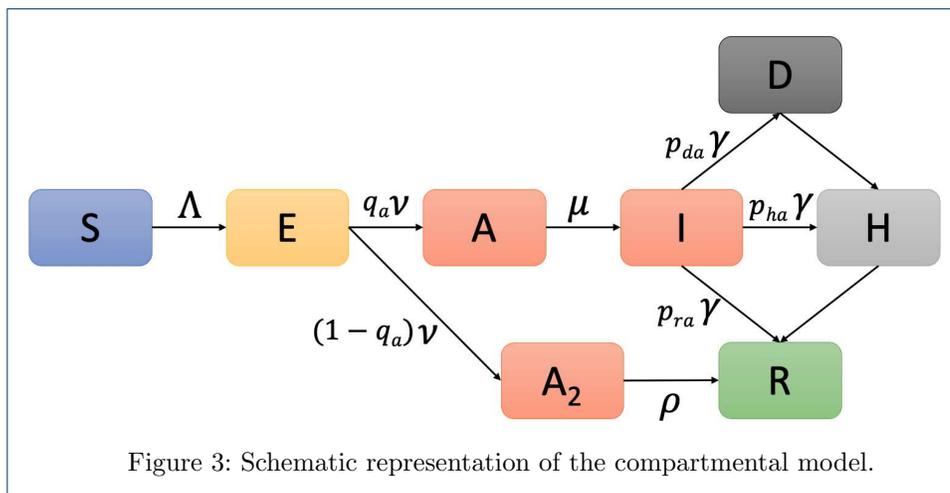
- **Ferry:** to transform port to port data into OA to OA, if movements exist between the two islands in the census, we increased the values of existing routes to match the ferry data volume as we expected these to represent the minimum true volume. We picked amongst the existing routes with a probability proportional to the relative commute traffic volume. If there were no existing connections between the islands in the commute census, we uniformly distributed to OAs on each island.

- **Skye bridge:** we assumed that there was one passenger per vehicle in winter. We further assumed that the increase in passenger flow over the bridge between seasons is proportional to the increase of passengers on ferry routes (on average 1.9x the volume). This is consistent with Transport Scotland statistics where the average occupancy of car in 2018 was found to be 1.5 (Transport Scotland, 2018); whilst our assumed winter and summer passenger volumes results is averaging 1.45 passengers per vehicle. The increased volume was then distributed between existing OA-OA routes in the census from the mainland to Skye with a probability proportional to the commute volume.
- **Airline:** no overlap with other sources of data was considered, movements from port to port were distributed between OAs using the same approach as for the ferry data.

Model

We used a stochastic network meta-population model, where each node represented an output area. Within each node we split the population into three age groups ([0-17), [17-70), and 70+) with populations derived from census data (Scotland’s Census, 2011). We modelled the disease state of each node’s population with a stochastic compartmental model including a latent (E) state, asymptomatic (A_2), presymptomatic (A) and symptomatic (I) infectious states, and subsequent hospitalised(H), recovered (R) or dead (D) states (schematic representation in Fig. 3).

To drive within-node infectious dynamics, we derived contact rates between individuals from age-structured mixing matrices based on survey data. For contacts before the pandemic we used POLYMOD matrices (Mossong et al., 2017), gathered before the pandemic, and for contacts during the pandemic we used CoMix matrices (Jarvis et al., 2020) gathered during the pandemic. The CoMix matrix we used gave a mean of 6 contacts per individual per day overall, consistent with other estimates of the highest mean number of contacts in the UK during the pandemic Christopher Jarvis, Amy Gimma, Kerry Wong, Kevin Van Zandvoort, John Edmunds (2020).



Further details regarding the implementation of the infection process in the model and the parameter values used are exposed in appendix.

Variation in the risk of introduction

We defined the *risk of introduction* before time t as the probability that at least one individual had entered one of the disease states (E , A , A_2 , I) before or at time t . As in Fig. 2, volumes of movements exhibited high variations depending on circumstances. The variation in risk of introduction between a typical summer and winter using the data from 2019 was therefore first explored. These periods being prior to the COVID-19 pandemic, the average number of contacts between individuals is defined by the POLYMOD age mixing matrix. A fixed prevalence was assumed on the mainland of 1%, which is approximately the prevalence estimated in Scotland by the ONS survey at the end of 2020 (ONS, 2020). We ran 200 simulations considering the winter edge weights and the summer edge weights respectively. As we are interested in short-term forecast here, the risk of introduction of the virus was calculated per island at 30 days after the start of the simulation, in summer and in winter.

We investigated statistical correlation of the introduction risk with network metrics, such as in-flow, closeness, betweenness, and length of the shortest path to mainland. The in-flow is the sum of the weights of incoming links (Wasserman *et al.*, 1994). The closeness is the average of the shortest path length from the node to every other node in the network (Freeman, 1978). The betweenness is the frequency with which a node is in the shortest path between pairs of nodes (Freeman, 1978). The shortest path between an island and the mainland in the weighted network is the path which minimises the sum of the inverse of the weights (here, the weights represent closeness, consequently the inverse of the weights are interpreted as a distance). The shortest path length is the sum of the inverse of the link weights which form the shortest path. We also considered other indicators such as population size, and the health and access domains of the Scottish Multiple Deprivation Index (SIMD, Scottish Government (2020)). SIMD is a relative measure of deprivation across datazones (DZs, which are areas containing approximately 500-1000 residents) in Scotland. SIMD looks at the extent to which an area is deprived across seven domains including health and access. The higher the score, the more deprived the area. The access domain is representative of the connectedness of the area taking into account drive or public transport travel time to facilities such as school, GP... The health domain measure the healthiness of the population. It has been shown to have a potential influence on COVID-19 mortality (Banks *et al.*, 2020).

Mitigation of the introduction risk

Relative importance of movement types

We used data from the summer 2020 to illustrate the movement pattern of a “pandemic summer”, where no travel restrictions were in place at the national level (ISSN International Centre, 2020). Despite the absence of restrictions the volumes of passengers between the islands was twice as low as the previous year, according to the ferry data. This can be explained by the implementation of quarantine for international travel in Scotland, which can discourage international movements, in addition to a change in behaviour (Brinkman *et al.*, 2020).

The risk of introduction before time t was defined as the probability that at least one individual has entered one of the disease states (E , A , A_2 , I) before time t or

at time t . To assess the importance of connections with neighbouring islands, we compared the conditional probability that an island k was infected given that one of its neighbours in the network was infected, with the probability the island k was infected.

The following notations were used to define the events of interest:

- event $I_{k,t}$: “introduction of COVID-19 on island k before or at time t ”
- event $N_{k,t}$: “introduction of COVID-19 on one of the neighbours of island k before or at time t ”

The probability of introduction of COVID-19 on island k before time t , $P(I_{k,t})$, was calculated as the ratio between the number of simulations with introduction in k before time t and the number of simulations.

The probability of introduction of COVID-19 on island k before time t given that COVID-19 has been introduced on at least one of the neighbouring islands $P(I_{k,t}|N_{k,t})$ was calculated as the number of simulations with introduction in k and any neighbour of k before time t divided by the number of simulations with introduction in any neighbour of k before time t , $\frac{P(I_{k,t} \cap N_{k,t})}{P(N_{k,t})}$.

We ran simulations considering the “summer 2020” level of movements and a mean of 6 contacts per person and day, and calculated the values of these two probabilities over time. To highlight any dependence between the probability for an island to get infected, and the probability for one of its neighbours to get infected, we compared $P(I_k)$ and $P(I_k|N_k)$. Finally, we considered situations in which restrictions would induce a reduction of 50% of the volume of movements from the mainland only, or a 50% reduction of movements from the mainland and between the islands. In the latter a larger volume of movements was therefore removed. We compared the effect of these two scenarios on the risk of introduction per island over time.

Delay in introduction according to restriction level

To assess the effect of movement restrictions on the risk of introduction, we compared the spread of COVID-19 obtained from simulations of the model with and without movement reductions. We focused on short-term projections and calculated the probability of case importation per island predicted after 30 days of simulation in the baseline scenario without movement restrictions. We then computed the time delay needed to reach the same value of introduction probability per island in simulations with movement restrictions.

We ran two scenarios considering a decrease of the movement volume from the mainland of 50% or 70%. We tested correlation between the number of movements removed and the delay observed in virus introduction per island.

Summary of the COVID-19 cases on the islands

We compared our results to PCR test results data from PHS (PHS, 2020), which provides per test performed the date of the test and the home DZ of the person tested. We tested the correlation between the number of months per island having at least one positive test and the probability of introduction calculated at 30 days in the “summer 2020” simulations.

Exploring control scenarios

We explored scenarios of control after introduction, with the aim at comparing the effect of controlling movements between OAs, as compared to controlling the number of contacts within OA, as well as the combination of these two measures.

Table 1: Table summarising the measures implemented for control in each scenario.

	Scenario 1a	Scenario 1b	Scenario 2	Scenario 3
Movement	No movement reduction	Movements from the mainland reduced by 50%	Movements from the mainland reduced by 50%	All movements reduced by 50%
Mean contacts	3	3	-	2.6

Our baseline was summer 2020, when the average number of contacts per individual per day was 6. In the different scenarios, the simulation started with the same disease parameters and movement network as the baseline. Control measures were implemented at 20 days. We considered, in scenario 1a, a decrease of the number of contacts from 6 to 3, which corresponds to the decrease observed in England when all public places inducing mixing were closed except for schools (Jarvis *et al.*, 2021). In scenario 1b, we considered movement restrictions, applied to movement from the mainland only alongside contact mitigation. In scenario 2, we explored the effect of controlling the movements from the mainland alone by reducing them by 50%. Finally the scenario 3 simulated a lockdown-like situation, decreasing average number of contacts down to 2.6, similar to observations in March 2020 (Jarvis *et al.*, 2020, 2021), and all movements reduced by 50%.

To compare the impact of these measures, for each scenario we reported the distribution of the number of individuals across simulations who has been infected in the whole of the Hebrides.

Results

Comparison of seasonal risks

The risk of importation to an island was estimated as the probability that at least one island inhabitant had become infected at 30 days of simulation or before. We first assessed correlations between introduction risk and network metrics in summer and winter, as well as with population size and two domains of the SIMD (Cf Table 2).

In-flow as weighted in-degree and shortest path length to mainland as minimum geodesic distance to the mainland were the measures showing the strongest correlation to risk. All other variables were significantly correlated apart from the *betweenness* and *closeness*. The variable *access* showed a negative correlation with the risk of introduction (-0.67 in winter, p-value 0.002, -0.65 in summer p-value 0.003), which is expected, since a higher access score means a longer driving/public transport time to facilities such as GP, schools or post office, i.e. poorer access. The variable *health* showed a positive correlation with the introduction risk in winter (0.54 p-value 0.022), indicating that areas with poorer health could be exposed to higher risk of introduction in winter.

Table 2: Spearman correlation between introduction risk and network metrics, population size, health and access domains from SIMD. (SPL: Shortest Path Length).

Variable	Winter		Summer	
	Correlation	p-value	Correlation	p-value
In-Flow	0.78	< .001	0.73	< .001
SPL to mainland	-0.75	< .001	-0.78	< .001
Population size	0.66	< .001	0.52	0.02
Access	-0.67	0.002	-0.65	0.003
Health	0.54	0.022	0.41	0.09

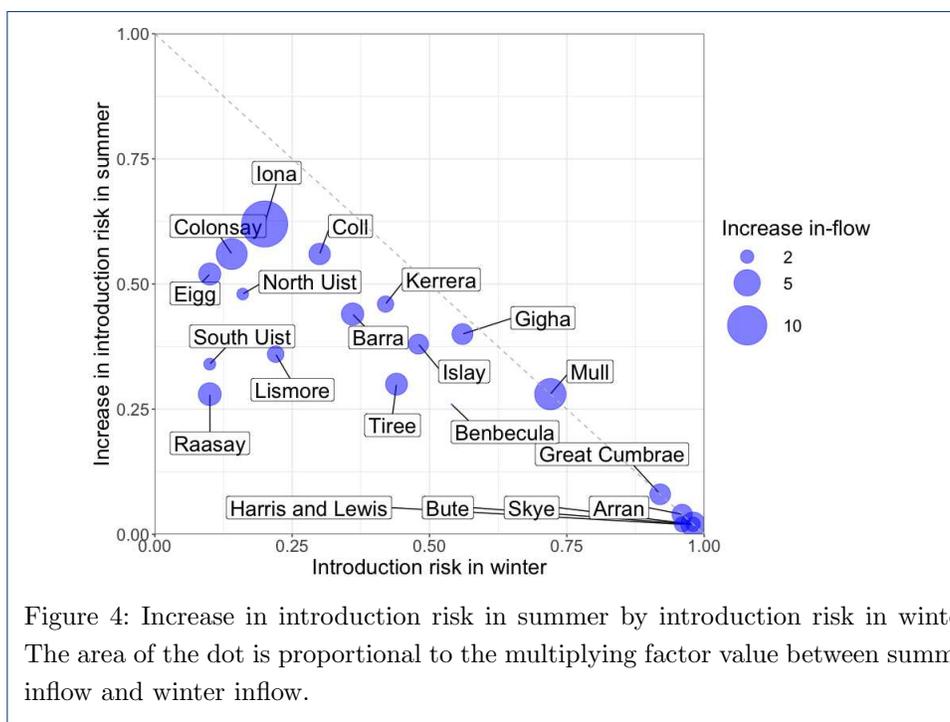


Figure 4: Increase in introduction risk in summer by introduction risk in winter. The area of the dot is proportional to the multiplying factor value between summer inflow and winter inflow.

Conditional probability and consequences for control

Relative importance of movements

Fig. 5 shows the probability for each island to introduce the virus over time (in red), and the conditional probability for these islands to introduce the virus given

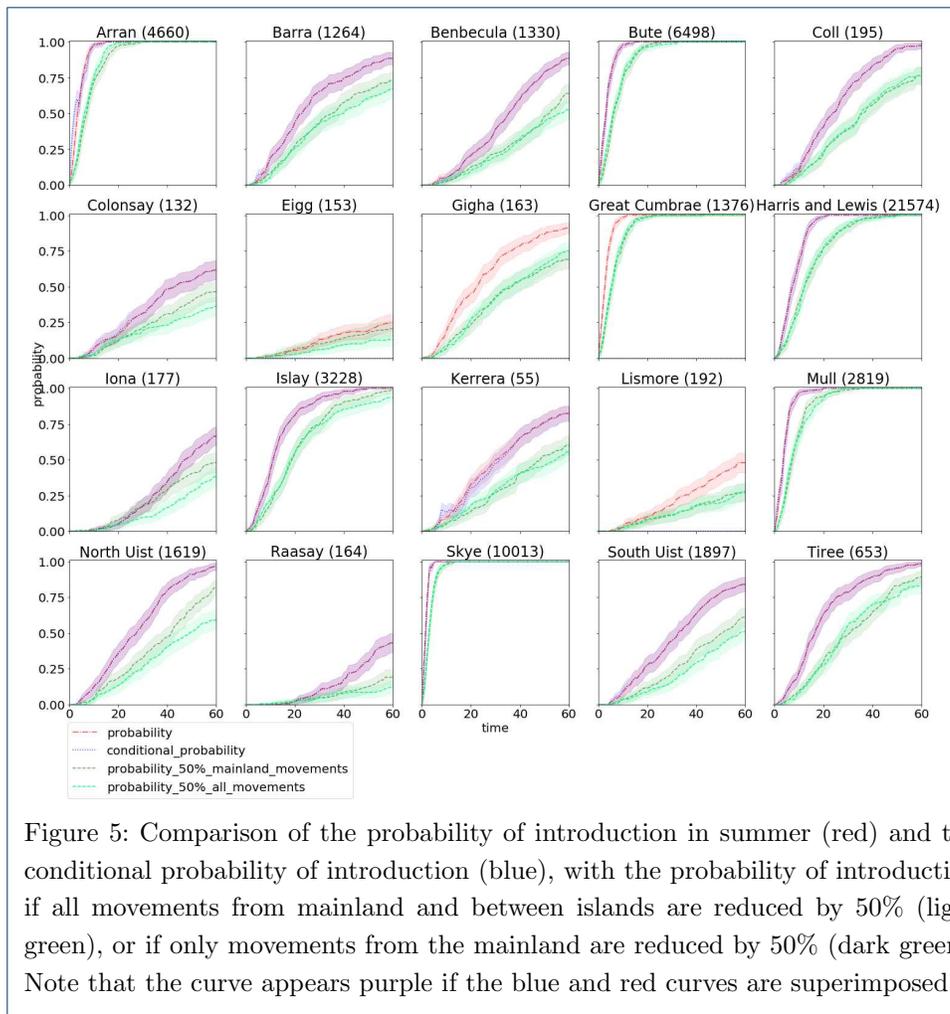


Figure 5: Comparison of the probability of introduction in summer (red) and the conditional probability of introduction (blue), with the probability of introduction if all movements from mainland and between islands are reduced by 50% (light green), or if only movements from the mainland are reduced by 50% (dark green). Note that the curve appears purple if the blue and red curves are superimposed.

that at least one of their neighbour has introduced the virus (in blue). The limited differences between the two probabilities suggest that the event introduction of COVID-19 on island k before time t is independent to the event introduction of COVID-19 on one of the neighbours of island k before time t .

Secondly the impact on the introduction risk of controlling certain movements is evaluated: movements from the mainland and between islands concomitantly are reduced by 50% (light green, scenario a), or movements from the mainland only are reduced by 50% (dark green, scenario b) Fig. 5. Scenario a leads to a larger number of movements being suppressed compared to scenario b . Despite a larger reduction of movements in scenario a , the effect on introduction risk is very similar between the two scenarios.

Delay observed following restrictions

We considered a reduction by 50% and 70% of the movements from the mainland, where the summer 2020 constitutes the baseline of the scenario.

A cluster analysis using the k-means method allowed us to distinguish two groups of islands (see Fig. 6), the clustering explaining 77.2% and 77.1% of the group's differences for the 50% and 70% reduction scenarios respectively. When movements

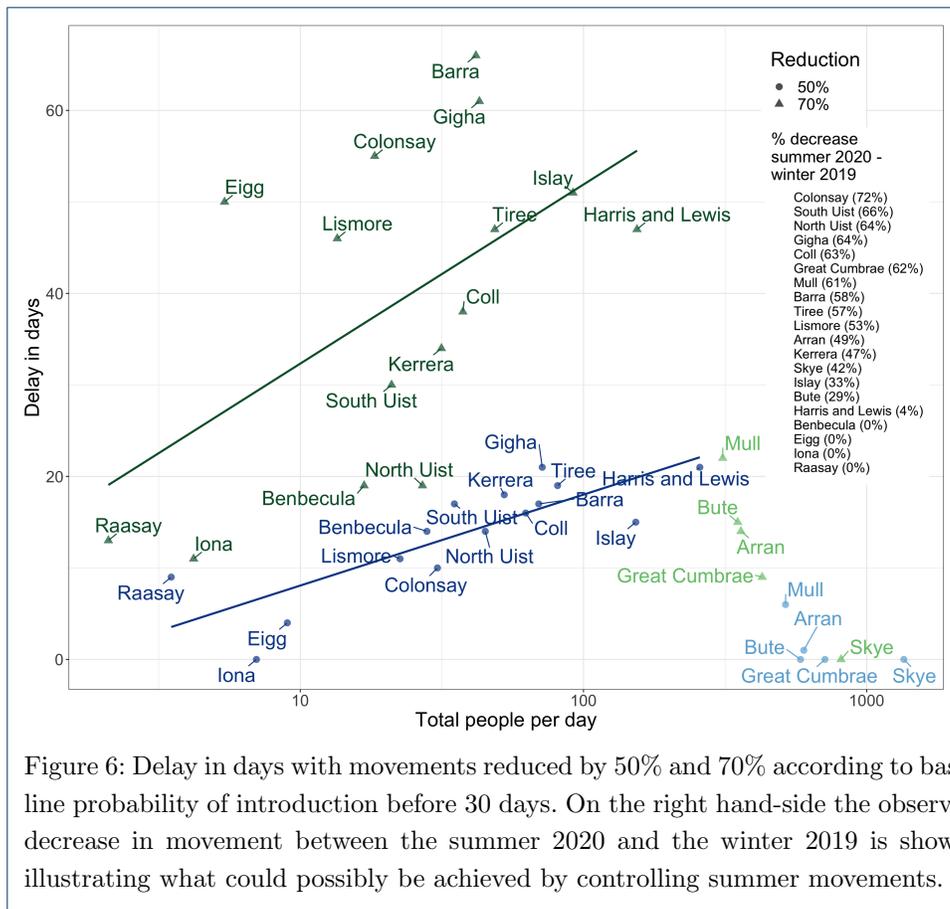


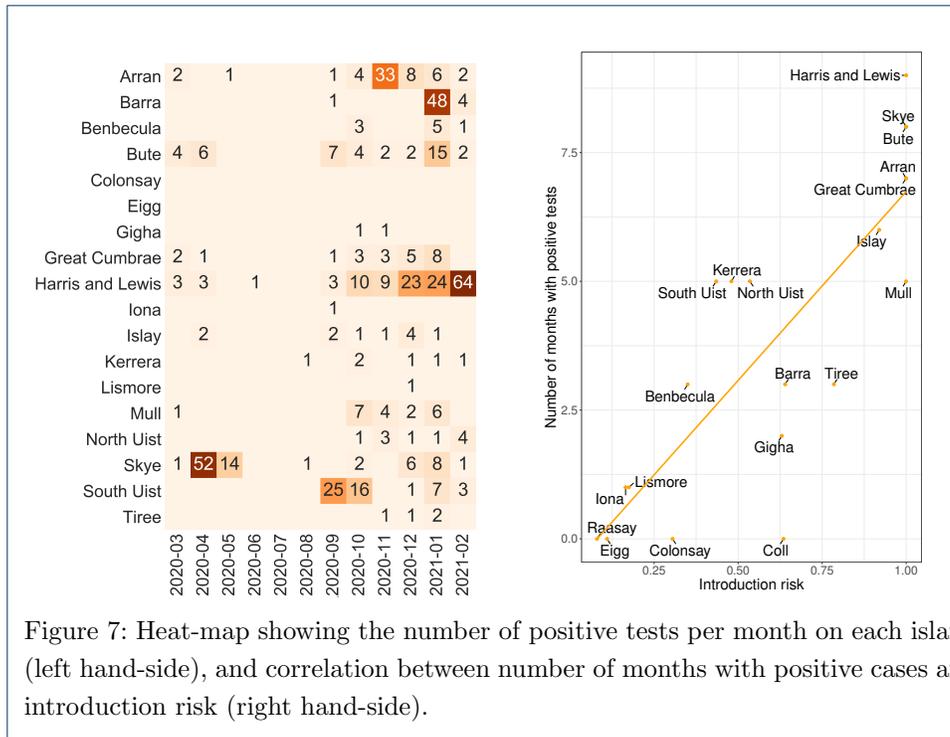
Figure 6: Delay in days with movements reduced by 50% and 70% according to base-line probability of introduction before 30 days. On the right hand-side the observed decrease in movement between the summer 2020 and the winter 2019 is shown, illustrating what could possibly be achieved by controlling summer movements.

were reduced by 50%, there was a strong linear correlation between the reduction in the number of passengers and resulting delay in days (Pearson correlation 0.78, p-value < .001) in the larger cluster of islands, as shown by the regression line. In the smaller cluster, although the decrease in number of passengers is higher there was nearly no delay in the introduction. This suggests that above a certain value, changes in movement volume have little impact, as the risk of introduction remains high.

The advantage of restricting movements varied between islands. For a number of islands like Barra, Gigha, Colonsay, there might be a real advantage of doing so, since we see a simulated delay of approximately two months. This means that the restriction would postpone the introduction beyond the length of an average summer holiday period, which also corresponds to a high risk period due to increased tourism activities. Beyond this period, the risk would spontaneously decrease with the seasonal decrease in movements.

Summary of the COVID-19 cases on the islands

COVID-19 has been introduced at several occasions on the islands since the start of the pandemic. The color matrix Fig. 7 shows the number of positive tests per island per month between March 2020 and February 2021. We assumed that positive tests on different months potentially corresponded to independent introductions. We



showed that there was a positive correlation between the number of introductions on each island and the baseline probability of introduction before 30 days calculated for summer 2020 (Pearson correlation 0.81, p-value < .001).

Exploring control scenarios

Fig. 8 highlights the difference in the distribution of the number of individuals who have been infected during the simulation according to the scenario considered.

Scenarios involving a reduction of the number of contact only (scenario 1a) were more effective than scenarios involving control on movements only (scenario 1b). This is to be expected as movements play an important role in spreading a disease to new places, but for COVID-19 once the pathogen has been imported, the circulation among smaller communities will be sufficient to sustain the epidemic provided that the number of recovered and immune individuals remain low.

Scenario 1b which was a combination of scenario 1a and 2, results in fewer infected individuals at the end of the simulation, but the decrease observed was not as great as the decrease between the two individual scenarios. This indicates that there is not a synergy when combining the two types of measure but some overlap in the disease transmission effect induced by each of those.

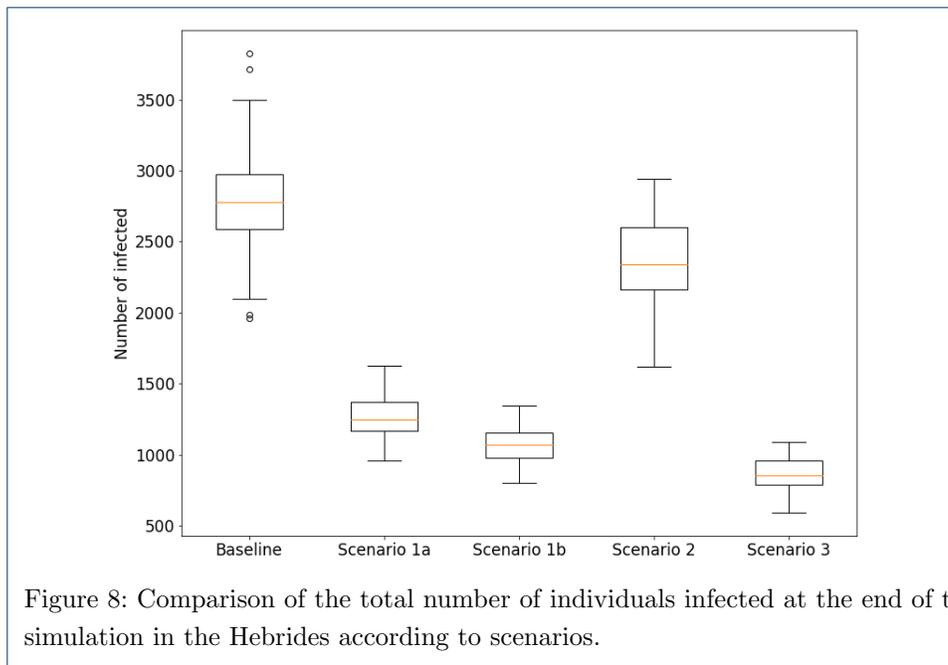


Figure 8: Comparison of the total number of individuals infected at the end of the simulation in the Hebrides according to scenarios.

Discussion

Movements play a crucial role in the spread of respiratory disease between territories. Our study provides important information on the seasonal variation of risk and effect of control measures that can help decision making and preparedness to such events.

Our analysis on the seasonal variation of risk showed that a number of islands (Skye, Bute, Arran, Great Cumbrae, Harris and Lewis) would have a high exposure to COVID-19 introduction from the mainland in summers and winters should the volumes of traffic be similar to “normal”, and the prevalence around 1% on the mainland. For these islands the risk remains high even in winter when fewer people are moving from the mainland and between islands. Yet COVID-19 might become a seasonal respiratory infection (Audi et al., 2020) in temperate areas. In this case annual epidemics of such respiratory disease would affect the human population in the winter season, when environmental parameters and changes in human behavior become more favourable for the spread (Moriyama et al., 2020). This would be especially of concern since other respiratory infections circulate at the same time, such as flu (Nelson and Holmes, 2007), which consequently increases the bed occupancy during winter months (Bouscambert et al., 2015). The potential impact on hospitals could be more severe in isolated areas like the Hebrides. In the UK, the vaccination against COVID-19 should be completed over summer 2021 (UK Government, 2021), but the risk of the emergence of a new variant escaping the vaccine will remain until then, and the risk of importation, beyond (Domingo and Perales, 2021, Koyama et al., 2020). If and when there is evidence of an escape mutant circulating, additional measures in areas exposed to a higher risk should be considered. Furthermore, the correlation between health index and introduction risk in winter highlights that those islands the most at risk in winter are also the ones that are the most deprived on the health level supporting the need for additional measures.

Our results also showed that movements from the mainland are more likely to play a role in the dissemination to new areas compared to movements from neighbouring islands (see Fig. 5). Consequently, in order to mitigate the risk of COVID-19 importation to the islands, restriction measures could primarily focus on reducing the passenger volume from the mainland but otherwise allowing continued traffic between islands with no restrictions.

In addition when movements from the mainland are reduced by 50%, some islands see the introduction of the virus delayed and the length of the delay is proportional to the decrease in number of passengers visiting the island. However, for a few other islands (Arran, Bute, Great Cumbrae, Mull and Skye) barely any delay is induced by the movement reduction. It is important to note that since the chosen prevalence on the mainland is 1%, if more than a thousand individuals are moving from the mainland to one of the island every day, it means that the probability to infect an individual on the island would be close to one every day. Therefore the islands that are highly connected to the mainland and experiencing a higher risk would not see any delay in the virus importation with a decrease of 50% of the mainland movements, since the volume of movements remains high enough to induce a high risk.

Finally our study suggests that the importation of the virus to the islands could be delayed by up to two months if movements from the mainland were reduced by 70% compared to the volume observed in summer 2020. This delay of two months should not be neglected in a period of massive vaccination. According to their vaccine delivery plan, the UK aims at vaccinating at least 2 million people per week from the end of January 2021 (UK Government, 2021). This means that any week of delay not only corresponds to time saved, but also to a higher vaccination coverage in the population. In addition, as the level of movements considered in the baseline scenario corresponds to a summer holiday period, the results show that for some islands a movement mitigation is likely to postpone the introduction of COVID-19 beyond the end of the holiday period, after which the risk will potentially decrease with the lower seasonal winter volume of travel. For those islands which could benefit from such a gain, it might be interesting to consider controlling movement during holiday periods to maintain the risk at a low level.

The parameters used in the model were taken from other COVID-19 studies in the UK or elsewhere. These parameters, especially the number of contacts per person and per day was set as the same for all areas, whereas in reality some areas will be more rural, less populated than others. These differences might be especially important in the case of islands which are generally less populated. Using the same parameters as the ones estimated in urban areas might introduce a bias. In addition the prevalence on the mainland was arbitrarily fixed and does not take into account the change in circulation level of COVID-19 over time. However, the calculated probability of introduction before 30 days showed a strong correlation with the number of months with positive tests on each of Hebrides, which reinforces the confidence in the reliability of the method and the results.

Movement restrictions during peak periods might not be viable economically for the islands. According to the National Plan for Scotland's Islands published in 2019 by the Scottish government, sustainable economic development can be achieved

through economic drivers such as marine activities, agriculture and crofting, fishing, tourism and the food and drink industry (Scottish Government, 2019). Most of these activities depend on free movement of people, essentially seasonal workers and tourists. Further investigations into the economic impact of these restrictions would have to be conducted to balance disease and economic risks for the population. These impacts must be taken into account in policy decisions to insure the prosperity of the island communities.

Conclusions

First, our results showed that Hebrides islands closely connected to the mainland could be exposed to a high introduction risk even over winter when mobility of people is low. This will be of concern as COVID-19 is likely to become a seasonal respiratory infection affecting temperate areas in winter. The spread of COVID-19 would be concomitant with other seasonal infections such as flu, increasing the pressure on health care services.

In addition, we found that for some islands, control of movements in peak summer tourist season has the potential for delaying the introduction risk for more than six weeks i.e. beyond the summer holiday period which is a period of high mobility of people potentially inducing a risk for rapid spread. Control of movements could be considered in the emergence of a new variant escaping the vaccine to protect the local community, but movement restrictions would be implemented at the expense of the economic growth which results from freedom of movements.

Appendix

The parameters used in the simulations are detailed in Table 3.

Table 3: Parameters

Parameter	Meaning	Value	Ref
$\frac{1}{\nu}$	Latent period	5.13 days	(More et al., 2020)
$\frac{1}{\rho}$	Asymptomatic infectious phase length	7 days	(Byrne et al., 2020, He et al., 2020)
$\frac{1}{\mu}$	Presymptomatic infectious phase length	2.5 days	(More et al., 2020, Byrne et al., 2020)
$\frac{1}{\gamma}$	Symptomatic infectious phase length	7 days	(Byrne et al., 2020, He et al., 2020)

To describe the infection process we used the following notations:

- $p = 0.05$ the infection probability of a contact between an infectious person and a susceptible person
- $A_{u,k}$ is age class k at node u .
- $X_t(A_{u,k})$ where X is a compartment in the compartmental model is the number of individuals in compartment X in age class A_k in node u at time t
- $N_t(A_{u,k})$ is the total number of individuals in age class A_k in node u at time t
- $\mathcal{I}_t(A_{u,k})$ is the number of individuals in *any* infectious compartment in age class A_k in node u at time t

- $p_{t,\mathcal{I}}(A_{u,k}) = \frac{\mathcal{I}_t(A_{u,k})}{N(A_{u,k})}$ is the proportion of age class A_k in node u at time t that is infectious, and as $p_{t,S}(A_{u,k}) = \frac{S_t(A_{u,k})}{N(A_{u,k})}$ the proportion of age class A_k in node u at time t that is susceptible
- C is a matrix describing contact between age classes, where $C_{i,j}$ is the expected number of contacts that an individual in age class A_i has with an individual in age class A_j .

The number of infectious contacts at node u is calculated by first generating for each infected person in $A_{u,j}$ how many contacts this person had with people in $A_{u,i}$. We randomly sampled from a Poisson distribution, $\mathcal{P}(y_{t-1}C_{i,j})$. Then for each infectious person, and its random number of contacts *contacts*, we randomly sampled from a hypergeometric distribution (the hypergeometric distribution is used instead of binomial because we assumed the contacts are with unique people, hence the random sampling must be done without replacement), with parameters *Hypergeometric*($N_t(A_{u,i}), S_t(A_{u,i}), \text{contacts}$), i.e. we sample *contact* times in the total population of node u , with a "success" being a susceptible person. These potentially infectious contacts for all people are then summed.

The number of between node infectious contacts at time t is calculated by first randomly sampling the number of commutes originating from infectious people in u , using a Binomial distribution,

$$\text{commutes from infectious}_t \sim \text{Bin}(p_{t-1,\mathcal{I}}(A_u), x_{t-1} * w(u, v))$$

Then given a number of such commutes, we selected those that targeted susceptible people in v .

$$\text{commutes from infectious to susceptible}_t \sim \text{Bin}(p_{t-1,S}(A_v), \text{commutes from infectious}_t)$$

After adding the number of within-node and between-node potentially infectious contacts, we sampled the number of new infections from a Binomial distribution:

$$\text{infectious contacts}_t \sim \text{Bin}(\text{contacts}_t, p)$$

The code for the model framework is publicly available: https://github.com/ScottishCOVIDResponse/simple_network_sim/.

List of abbreviations

DZ: Data Zone

NPIs: Non-Pharmaceutical Interventions

OA: Output Area

SIMD: Scottish Index for Multiple Deprivation

SPL: Shortest Path Length

UK: United Kingdom

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication
Not applicable

Availability of data and materials
The datasets used during the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

Funding
This work was partially funded by the Scottish Government Rural and Environment Science and Analytical Services Division, as part of the Centre of Expertise on Animal Disease Outbreaks (EPIC), the PhD PCDS fund (University of Edinburgh) and the Roslin ISP2 (theme 3) - BBS/E/D/20002174 (Roslin Institute). The funders provided support in the form of salaries for the authors [ASR and CB], but did not have any additional role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Author's contributions
ASR performed the data cleaning and manipulation, as well as the analysis, under the supervision of JE, CB, and RRK. ASR wrote the initial manuscript draft. All authors have read and approved the manuscript. RRK is the author for correspondence.

Acknowledgements
The authors would like to thank Calmac for providing data on ferry crossings and passenger numbers, Transport Scotland for road usage statistics and the electronic Data Research and Innovation Service within Public Health Scotland (<https://www.isdscotland.org/Products%2Dand%2DServices/EDRIS/>) for provision of data.

Author details

¹The Roslin Institute, University of Edinburgh, Easter Bush Campus, Edinburgh, Scotland. ²School of Computing Science, University of Glasgow, G12 8QQ Glasgow, Scotland. ³Royal (Dick) School of Veterinary Studies, University of Edinburgh, Edinburgh, Scotland.

References

- Leslie A Reperant and Albert DME Osterhaus. Aids, avian flu, sars, mers, ebola, zika... what next? *Vaccine*, 35 (35):4470–4474, 2017.
- National Records of Scotland. Deaths involving coronavirus (covid-19) in scotland week 14 (30 march to 5 april 2020), 2020a. URL <https://www.nrscotland.gov.uk/files/statistics/covid19/covid-deaths-report-week-14.pdf>.
- National Records of Scotland. Deaths involving coronavirus (covid-19) in scotland week 29 (13 to 19 july 2020), 2020b. URL <https://www.nrscotland.gov.uk/files/statistics/covid19/covid-deaths-report-week-29.pdf>.
- Samantha J Lycett, Joseph Hughes, Martin P McHugh, Ana da Silva Filipe, Rebecca Dewar, Lu Lu, Thomas Doherty, Amy Shepherd, Rhys Inward, Gianluigi Rossi, et al. Epidemic waves of covid-19 in scotland: a genomic perspective on the impact of the introduction and relaxation of lockdown on sars-cov-2. *medRxiv*, 2021.
- Sophie Cousins. New zealand eliminates covid-19. *The Lancet*, 395(10235):1474, 2020.
- Chiara Poletto, MF Gomes, A Pastore y Piontti, Luca Rossi, Livio Bioglio, Dennis L Chao, IM Longini Jr, M Elizabeth Halloran, Vittoria Colizza, and Alessandro Vespignani. Assessing the impact of travel restrictions on international spread of the 2014 west african ebola epidemic. *Eurosurveillance*, 19(42):20936, 2014.
- Ana LP Mateus, Harmony E Otete, Charles R Beck, Gayle P Dolan, and Jonathan S Nguyen-Van-Tam. Effectiveness of travel restrictions in the rapid containment of human influenza: a systematic review. *Bulletin of the World Health Organization*, 92:868–880D, 2014.
- UK data service. Census flow data, 2011. URL <https://census.ukdataservice.ac.uk/get-data/flow-data>.
- Civil Aviation Authority. Uk airport data, 2020. URL <https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-airport-data/>.
- QGIS Development Team. *QGIS Geographic Information System*. Open Source Geospatial Foundation, 2020. URL <http://qgis.osgeo.org>.
- R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2020. URL <https://www.R-project.org/>.
- ISSN International Centre. Coronavirus (covid-19) phase 3: Scotland's route map update - 9 july 2020, 2020. URL <https://www.gov.scot/publications/coronavirus-covid-19-framework-decision-making-scotlands-route-map-through-out-crisis-phase-3-update/pages/6/>.
- Transport Scotland. Car occupancy, percentage of car stages 1 by car occupancy, 2008-2018, 2018. URL <https://www.transport.gov.scot/publication/transport-and-travel-in-scotland-results-from-the-scottish-household-survey-1/table-td9-car-occupancy-percentage-of-car-stages-1-by-car-occupancy-2008-2018-2-3>.
- Scotland's Census. Output area, 2011. URL <https://www.scotlandscensus.gov.uk/variables-classification/output-area-2011>.
- Joël Mossong, Niel Hens, Mark Jit, Philippe Beutels, Kari Auranen, Rafael Mikolajczyk, Marco Massari, Stefania Salmaso, Gianpaolo Scalia Tomba, Jacco Wallinga, et al. Polymod social contact data. 2017.
- Christopher I Jarvis, Kevin Van Zandvoort, Amy Gimma, Kiesha Prem, Petra Klepac, G James Rubin, and W John Edmunds. Quantifying the impact of physical distance measures on the transmission of covid-19 in the uk. *BMC medicine*, 18:1–10, 2020.

- Christopher Jarvis, Amy Gimma, Kerry Wong, Kevin Van Zandvoort, John Edmunds. The effect of social distancing on the reproduction number and number of contacts in the UK from a social contact survey report for survey week 31, 2020. URL <https://cmmid.github.io/topics/covid19/reports/comix/CoMix%20Weekly%20Report%2031.pdf>.
- ONS. Coronavirus (covid-19) infection survey, UK, 2020. URL <https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurveysurvey/18december2020>.
- Stanley Wasserman, Katherine Faust, et al. Social network analysis: Methods and applications. 1994.
- Linton C Freeman. Centrality in social networks conceptual clarification. *Social networks*, 1(3):215–239, 1978.
- Scottish Government. Scottish index of multiple deprivation 2020, 2020. URL <https://www.gov.scot/collections/scottish-index-of-multiple-deprivation-2020/>.
- Christopher J Banks, Ewan Colman, Thomas Doherty, Oliver Tearne, Mark E Arnold, Katherine Elizabeth Atkins, Daniel Balaz, Gaël Beaunée, Paul Bessell, Jessica Enright, et al. Disentangling the roles of human mobility and deprivation on the transmission dynamics of covid-19 using a spatially explicit simulation model. *medRxiv*, 2020.
- Jeffrey C Brinkman, Kyle Mangum, et al. *The Geography of Travel Behavior in the Early Phase of the COVID-19 Pandemic*. Research Department, Federal Reserve Bank of Philadelphia, 2020.
- PHS. Public health Scotland, 2020. URL <https://www.isdscotland.org/Products%2Dand%2DServices/EDRIS/>.
- Christopher I Jarvis, Amy Gimma, Kevin van Zandvoort, Kerry LM Wong, and W John Edmunds. The impact of local and national restrictions in response to covid-19 on social contacts in England: a longitudinal natural experiment. *BMC medicine*, 19(1):1–12, 2021.
- Amani Audi, Malak Allbrahim, Malak Kaddoura, Ghina Hijazi, Hadi M Yassine, and Hassan Zaraket. Seasonality of respiratory viral infections: Will covid-19 follow suit? *Frontiers in Public Health*, 8:576, 2020.
- Miyu Moriyama, Walter J Hugentobler, and Akiko Iwasaki. Seasonality of respiratory viral infections. *Annual review of virology*, 7:83–101, 2020.
- Martha I Nelson and Edward C Holmes. The evolution of epidemic influenza. *Nature reviews genetics*, 8(3):196–205, 2007.
- M Bouscambert, M Valette, and B Lina. Rapid bedside tests for diagnosis, management, and prevention of nosocomial influenza. *Journal of Hospital Infection*, 89(4):314–318, 2015.
- UK Government. UK covid-19 vaccines delivery plan, 2021. URL <https://www.gov.uk/government/publications/uk-covid-19-vaccines-delivery-plan/uk-covid-19-vaccines-delivery-plan>.
- Esteban Domingo and Celia Perales. The time for covid-19 vaccination. *Journal of Virology*, 95(8), 2021.
- Takahiko Koyama, Dilhan Weeraratne, Jane L Snowden, and Laxmi Parida. Emergence of drift variants that may affect covid-19 vaccine development and antibody treatment. *Pathogens*, 9(5):324, 2020.
- Scottish Government. The national plan for Scotland's islands, 2019. URL <https://www.gov.scot/publications/national-plan-scotland-islands/pages/6/>.
- Simon John More, Conor G McAloon, John M Griffin, Miriam Casey, Ann Barber, Elizabeth Lane, Andrew W Byrne, Áine B Collins, David McEvoy, Kevin Hunt, et al. Covid-19 epidemiological parameters summary document. Technical report, Department of Health, 2020.
- Andrew William Byrne, David McEvoy, Aine B Collins, Kevin Hunt, Miriam Casey, Ann Barber, Francis Butler, John Griffin, Elizabeth A Lane, Conor McAloon, et al. Inferred duration of infectious period of sars-cov-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic covid-19 cases. *BMJ open*, 10(8):e039856, 2020.
- Xi He, Eric HY Lau, Peng Wu, Xilong Deng, Jian Wang, Xinxin Hao, Yiu Chung Lau, Jessica Y Wong, Yujuan Guan, Xinghua Tan, et al. Temporal dynamics in viral shedding and transmissibility of covid-19. *Nature medicine*, 26(5):672–675, 2020.