Manipulation of contact network structure and the impact on FMD disease transmission

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Introduction

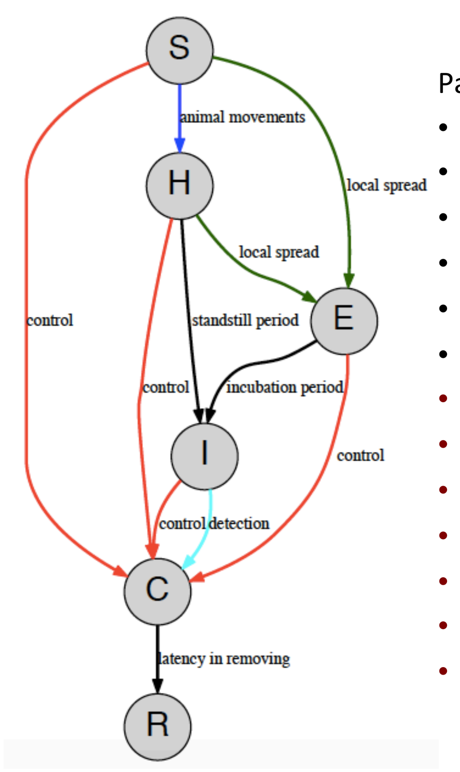
- The movements of livestock between individual premises and markets can be characterised as a dynamic network where the structure of the network itself can critically impact the transmission dynamics of many infectious diseases. As evidenced by the 2001 Foot-and-Mouth disease (FMD) epidemic in the UK, this can involve transmission over large geographical distances and can result in major economic loss [1,2]. Mandatory livestock movement restrictions were introduced: a 13-day standstill in Scotland for cattle and sheep after moving livestock onto a farm (with certain exemptions) and a 6-day standstill for cattle and sheep in England and Wales from 2003 (without any exemptions).
- An important consideration when contemplating legislative changes such as movement restrictions is the knock-on effect these could have on the emergent properties of the system, i.e. the network structure itself.
- We investigate how disease dynamics change when the local contact structure of the recorded livestock movement network in Scotland is altered through rewiring movements between premises.

Network Rewiring

The network rewiring algorithm changes the structure of the recorded livestock movement network through a combination of altered movement restrictions and redirection of movements between holdings and markets to avoid nonsensical activity (e.g. movements to markets on days when they are inactive) while conserving key characteristics (e.g. movement date and market sales of the correct animal production type).

- Cattle and sheep movements (1 month of data, CTS and Samu database
- Combinations of standstill length (6 days / 13 days), standstill exemption (yes / no), and market-rewire (yes / no)).
- Movements violating a standstill are pushed forward to the next legal date; Movements at next permissible date trigger a new standstill
- Exempt movements were identified and removed during rewiring before applying structural changes to the livestock movement network. These movements were reinserted at the final stage of rewiring.
- Disallowed market movements were pushed back to the next available market day of the same production type at the same market, or the nearest geographical market on the next available market day of the same production type

Stochastic FMD Model



Parameters

- Local transmission: 0.065 $farm^{-1}\,day^{-1}$
- Movements: <...>
- Incubation period: 5 days
- Standstills: 13 days
- Detection (by clinical signs): 3 days
- Control measures delay: 20
- Movement ban delay: 20
- Contact tracing depth: 21
- Remove farms within 0.5 km
- Delay (local): 1
- Delay (direct): 2
- Delay (market): 4

- Spatial model of FMD disease transmission and control through movements and local spread
- Initial outbreak, prior to detection of disease
- Consider both: initial spread and control

Results

(a) Standstill compliance.

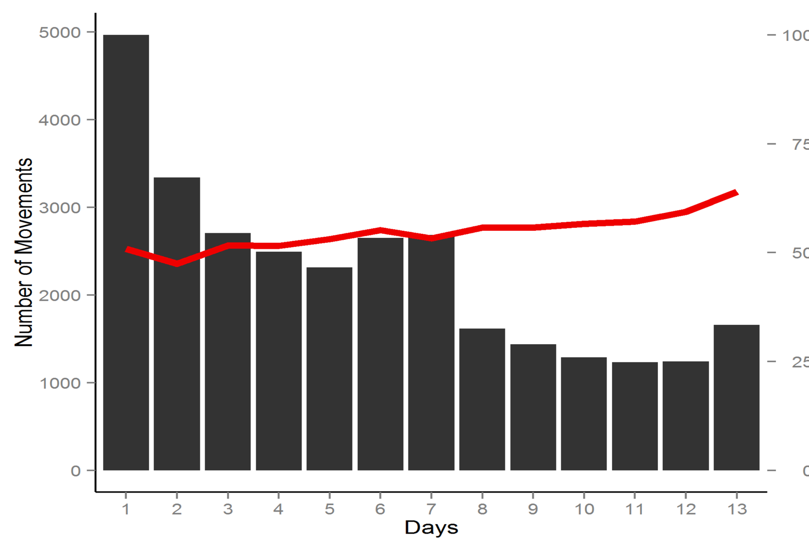


Figure 1. Frequency of combined sheep and cattle movements (2011-2013) during the standstill period, aggregated by waiting time after standstill regulations take effect. The right axis presents the percentage of proportion of exempt movements.

(b) Network Analysis.

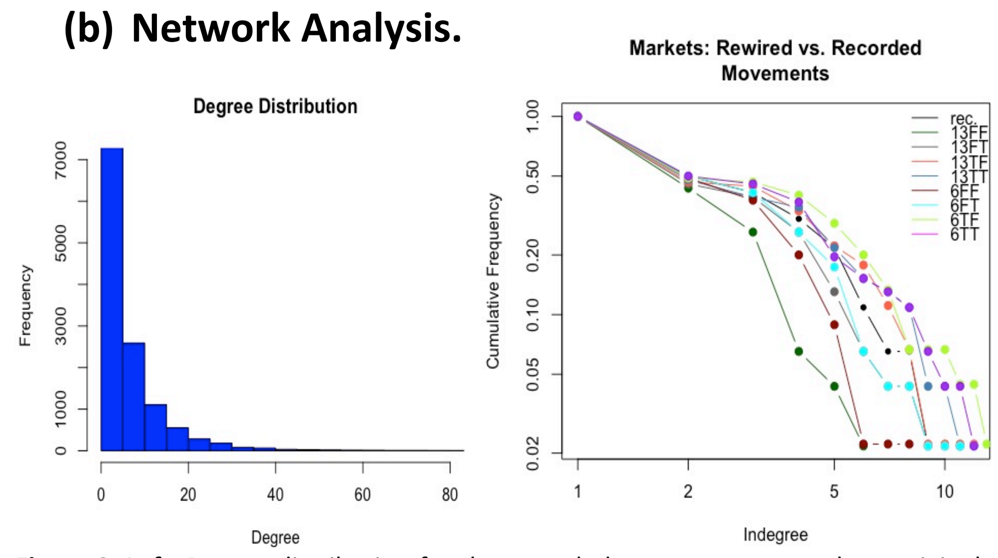


Figure 2. Left: Degree distribution for the recorded movement network on original scale. **Right:** The distribution of in-degrees of markets in the cattle / sheep network considering all nine scenarios, plotted on a log-scale. Names for each scenario were chosen so that the number at the beginning of each name represent the length of the standstill period applied to the respective scenario, followed by whether it had been rewired to the nearest market or not as indicated by binary categories (T = True / F = False), and finally whether standstill exemptions were allowed or not (T = True / F = False).

(c) FMD model output.

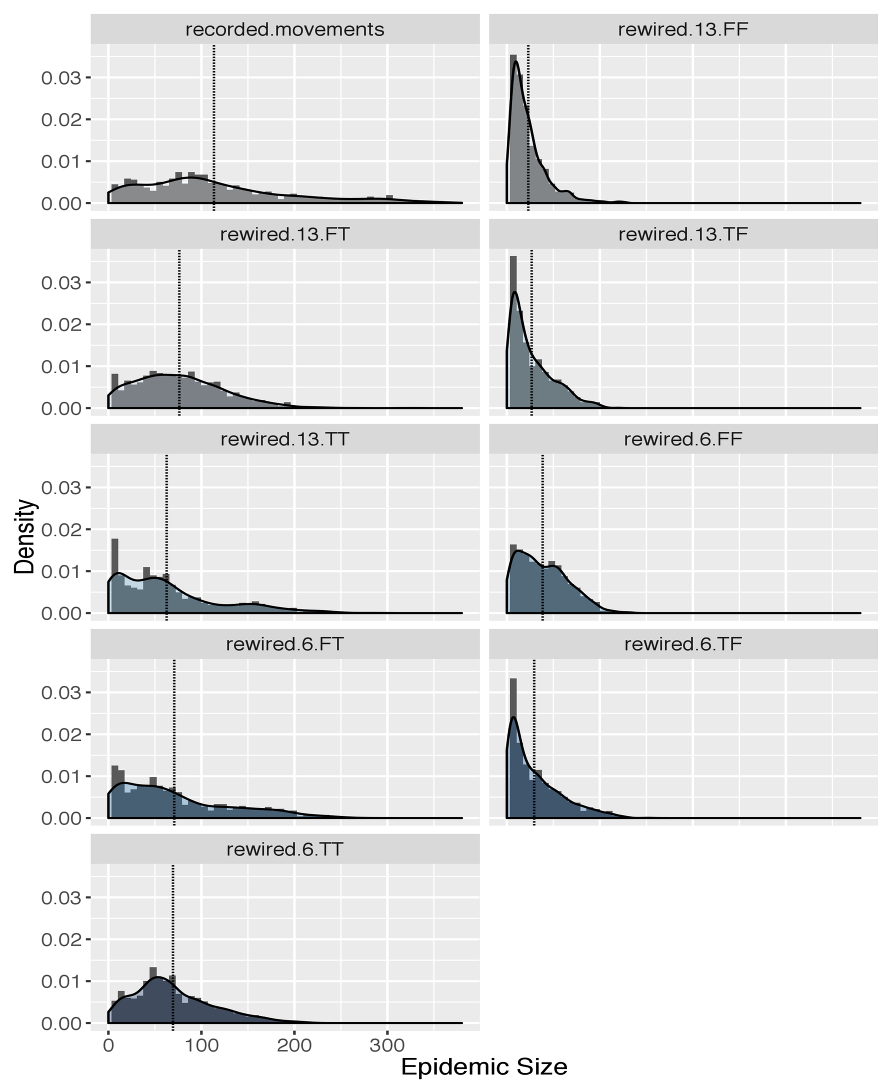


Figure 3. Histograms of final epidemic size overlayed by their density curve for the FMD simulation outputs on recorded movements (top left) and generated rewired networks. Left panel: All scenarios on the left allow exemptions (indicated by second T (=TRUE) in label). Length of standstill in days is indicated by '6' or '13'. Right panel: All FMD simulation outputs on rewired scenarios that do not allow standstill exemptions. The vertical line represents the median.

(d) Comparison of three scenarios.

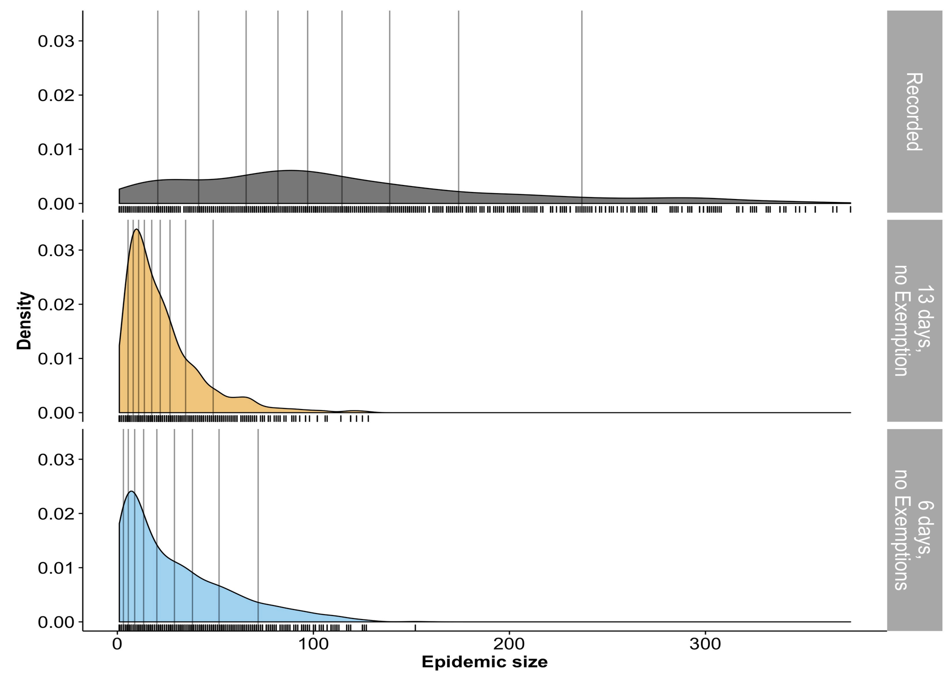


Figure 4. Kernel density estimates for the output of the FMD simulation on recorded movements (top), the rewired 'extreme' scenario of 13 days standstill with no exemptions (middle), and the rewired 'England-Wales' scenario of 6 day standstill with no exemptions (bottom), with vertical lines representing deciles.

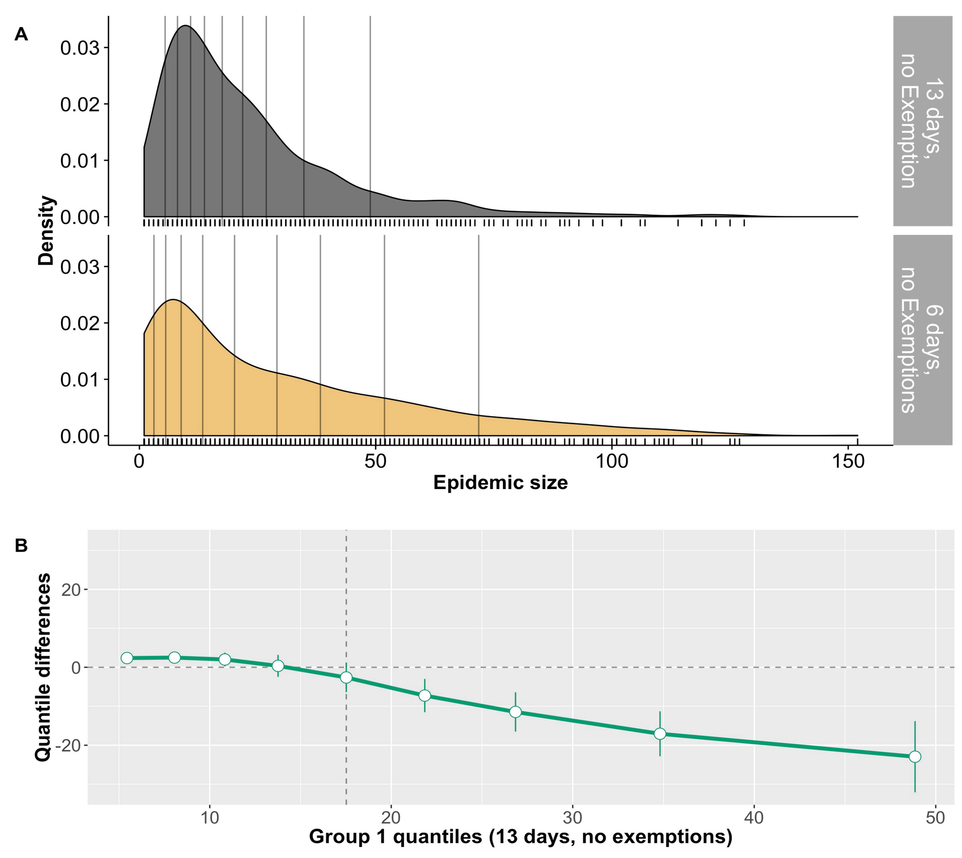


Figure 5. A. Kernel density estimates for the output of the FMD simulation on the rewired 'extreme' scenario of 13 days standstill with no exemptions (top), and the rewired 'England-Wales' scenario of 6 day standstill with no exemptions (bottom), with vertical lines representing deciles. **B.** Shift function. The difference of Group 1 (13 days, no exemptions) – group 2 (6 days, no exemptions) is plotted along the y-axis for each decile (white disks), as a function of group 1 deciles. For each decile difference, the vertical line indicates its 95% bootstrap confidence interval (1000 samples). When a confidence interval does not include zero, the difference is considered significant.

(e) Spatial effects.

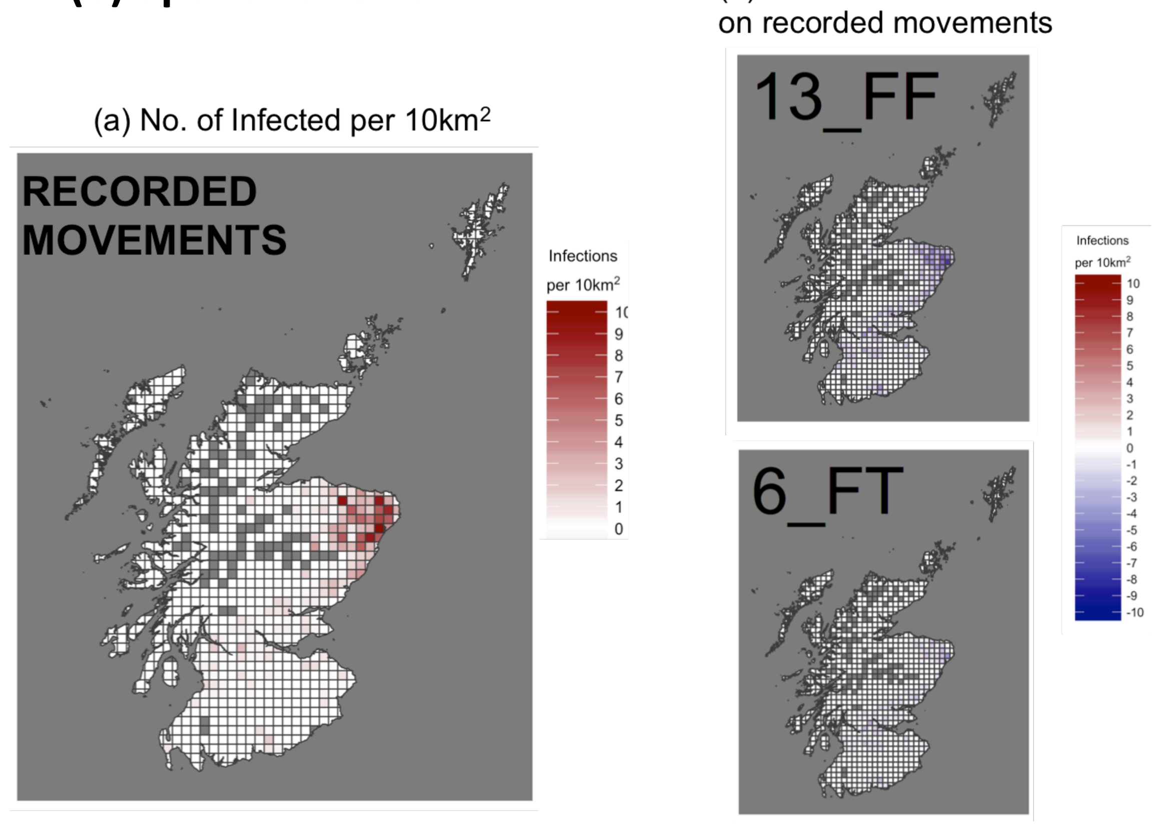


Figure 6. (a) Number of infections per 10km² for the FMD simulation on the originally recorded cattle and sheep movements. (b) Differences between the FMD simulations on recorded movements and the rewired 'extreme' scenario (13_FF, top right) and the rewired 'England / Wales – scenario' (6_FT, bottom right). Warmer colour denote an increase in counts, cooler colours denote a decrease of counts.)

Conclusions

There is obvious benefit from rewiring, resulting in networks with higher clustering coefficients and lower density, both decreasing the number of susceptible contacts compared to the recorded movement network.

- FMD outbreak simulations: As expected, rewiring leads to a decrease in outbreak size and - if standstill exemptions are prohibited – higher probability of smaller outbreaks; No 'market' effect;
- Without exemptions, a short 6-day movement standstill is almost as effective as a long standstill period of 13-days.
- Overall, a simpler biosecurity system with shorter standstills but no exemptions, which would likely be easier to legislate for and monitor, would offer no substantial additional risk for FMD. These results suggest that explicitly manipulating the contact network structure in a sensible way has the potential to significantly impact disease control.

References

[1] J.C. Gibbens et al. *Vet. Rec.* **149** (2001) 729–43.

[2] M.J. Keeling et al. *Science.* **294** (2001) 813–7.

[3] D.M. Green, I.Z. Kiss, R.R. Kao. *Proc. Biol. Sci.* **273** (2006) 2729–35.