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Multilayer network analysis of Scottish sheep/cattle movements for multi-host disease control

Introduction

- Network Analysis applied to livestock movements can help predict the course of epidemics (e.g. viral disease like Foot-and-Mouth Disease [1], or bacterial disease like Verotoxigenic Escherichia coli O157:H7 [2])
- The **betweenness** of a farm is the frequency with which a farm is in the shortest path between pairs of farms [3]
- High betweenness farms are more likely to spread disease to new 'communities' of farms [4]
- In Scotland, both cattle and sheep are often raised on the same farms, so there are many opportunities for diseases to 'jump' between them

Aim

- Highlighting the impact of combining sheep with cattle in a multilayer network vs. single-species network on the targeted farms for control or surveillance measures of multi-hosts disease

Data

- Cattle Tracing System: Cattle movements data, 2016
- ScotEID: Sheep movements data, 2016

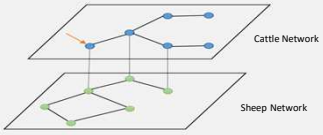

Fig. 1: Schema of the multilayer network, intralayer links (in black) represent livestock movement between farms, interlayer links (in grey) represent a permanent link between layers for mixed-species farms. The red arrow shows a farm with a significant betweenness change between the cattle and the multilayer network

Methodology

- Here we consider a fast spreading disease, with an equal probability of transmission between species. We consider only livestock movements as a spreading pathway, and exclude other possible transmission routes
- We analysed monthly, static, directed, unweighted
  - Sheep Networks
  - Cattle Networks
  - Multilayer Networks combining both species
- At each step the farm with the highest betweenness was removed, and the betweenness across the network recalculated
- We ranked the farms according to their betweenness, and compared the **100 "risky" farms**, i.e. 100 farms with the highest betweenness
  - Between months in the same network
  - Between the single-species network and the multilayer network for the same month

	Multilayer	Sheep	Cattle
Number of Farms	9,000	5,018	6,138
Proportion of mixed farms	49%	88%	72%
Number of movements	22,393	13,045	9,604
Density	0.401	0.384	0.639
Clustering coefficient	0.00308	0.00248	0.00182
Proportion of GSCC[1]	29.6%	22.0%	18.3%
Proportion of GWCC[2]	98.1%	99.0%	95.9%
Average path Length	3.86	4.04	0.399

Table 1 General characteristics of each Network
[1]Giant Strongly Connected Component
[2]Giant Weakly Connected Component

References

[1] Shirley (2005). Where diseases and networks collide: lessons to be learnt from a study of the 2001 foot-and-mouth disease epidemic. *Epidemiology & Infection*, 133(6), 1023–1032.
[2] Widgren (2016). Data-driven network modelling of disease transmission using complete population movement data: spread of VTEC O157 in Swedish cattle. *Veterinary Research*, 47(1), 81. https://doi.org/10.1186/s13567-016-0366-5
[3] Freeman (1979). Centrality in Social Networks Conceptual Clarification. *Social Networks*, 1(3), 215–239. https://doi.org/10.1016/0378-8733(78)90021-7
[4] Bell (1999). Centrality measures for disease transmission networks. *Social Networks*, 21(1), 1–21.

Results

- On average **46%** of the targeted cattle farms and **64%** of the targeted sheep farms per month are different for the multilayer network than the single-species network over 2016
- The Multilayer network is influenced by the seasonality of sheep and cattle networks (Fig. 2)
  - From September to October the risky farms in the multilayer network are more similar to the ones in the sheep network,
  - The rest of the year the risky farms in the multilayer network are more similar to the ones in the cattle network

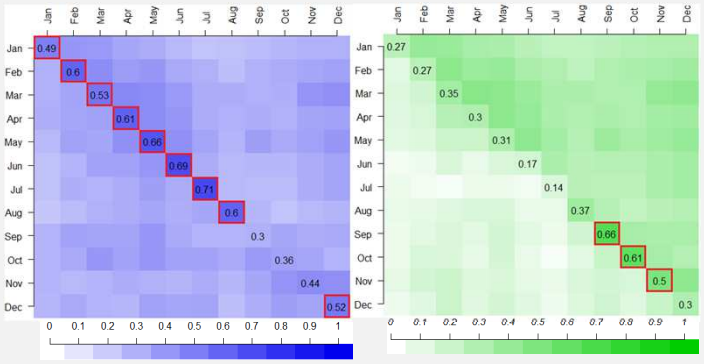

Fig. 2: Colour matrices of the **proportion of similar risky farms**
(i) Between months of Multilayer Network: Upper blue triangle and upper green triangles
(ii) Between months of Cattle network: Lower blue triangle
(iii) Between months of Sheep network: Lower green triangle
(iv) Between Sheep (green) / Cattle (blue) and the Multilayer network: Diagonal

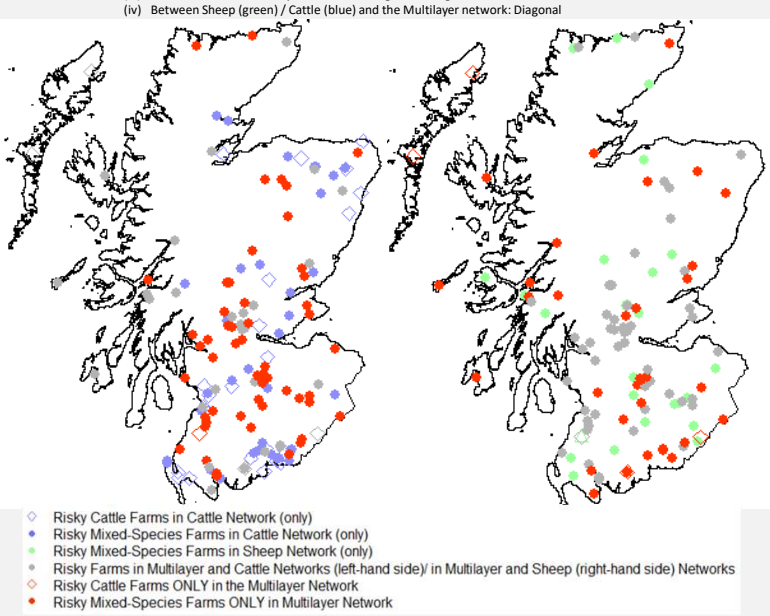

Fig. 3 Map highlighting the difference in risky farms that could be targeted for control measures, in the Cattle (left-hand side) or Sheep (right-hand side) vs. Multilayer Network for the month of October 2016

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
0.28	0.24	0.22	0.12	0.09	0.14	0.20	0.08	0.14	0.11	0.14	0.24	**0.17**

Table 2 Proportion risky farms in the multilayer network that are not risky in none of the single-species networks, per month in 2016

Conclusion

- The cattle and sheep networks are connected in Scotland, and influence one another. On average 17% of the risky farms in the multilayer network are not risky in none of the single-species networks, and would be missed if control measures are implemented without considering both species.

Next steps

- Confirming the result by simulating a disease spread, accounting for varying infectiousness values between species
- Considering alternative transmission routes (contact through pastures, aerosol spread…)