



Descriptive analysis of pig production pyramids in Great Britain, 2016 – 2018.

December 16, 2021

Document Information

Document information	
Species	Pig
Report reference	EPIC_202122_REP_001
Associated scoping document	EPIC_201617_SD_002V3
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Data source	Electronic Movement Licensing System for Pigs (eAML2), Scottish EID Livestock Traceability Research (ScotEID), APHA NM PRIMO register, APHA WR PRIMO register and APHA WB PRIMO register
Data year	2016-2018

Cover photo by: Carla Correia-Gomes, Animal Health Ireland, Carrick on Shannon, Ireland.

Acknowledgements

The authors gratefully acknowledge ScotEID for providing a copy of the Scottish Livestock Electronic Identification and Traceability database. Additionally, thank you to the Pork section of the Agriculture and Horticulture Development Board (AHDB-pork) for providing a copy of the electronic Animal Movement Licensing (eAML2) records. Both were supplied under data sharing agreements. The authors also thank the Animal and Plant Health Agency (APHA) for providing the electronic database of all breeding organisations registered under PRIMO for 2017, and the electronic databases providing all the 'Weaner-Rearer' and 'Weaner-Breeder' holdings registered under PRIMO in Great Britain. Additionally, APHA/Radar also kindly provided the 2013 pig keeper register to EPIC.

This work was funded by the Scottish Government Rural and Environment Science and Analytical Services Division (RESAS), as part of the Centre of Expertise on Animal Disease Outbreaks (EPIC).

Acronyms

Acronyms	Definitions
GB	Great Britain
UK	The United Kingdom
SG	The Scottish Government
RESAS	The Scottish Government's Rural and Environment Science and Analytical Services Division
APHA	The Animal and Plant Health Agency
EPIC	The Scottish Centre of Expertise on Animal Disease Outbreaks
PRIMO	The Pigs (Records, Identification and Movement) Order 2011
MRZ	Movement Restriction Zone
CPH	County-Parish-Holding identifier
ScotEID	The Scottish Livestock Electronic Identification and Traceability database
eAML2	The Electronic Animal Movement Licensing System
NM	Nucleus-Multiplier
WR	Weaner-Rearer
WB	Weaner-Breeder
M-GO	Multiplier-Grow Out
NM-GO	Nucleus-Multiplier-Grow Out
M-GiltMU	Multiplier-Gilt Mating Unit
M-GiltMU	Nucleus-Multiplier-Gilt Mating Unit
T1, ..., T4	Tier 1 holding, ..., Tier 4 holding
NR	Non-registered pyramid
NA	Non applicable
N	Total number

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Executive summary

Objectives

- Characterise pyramids in Great Britain (GB), including the number of farms involved and their geographical distribution;
- Describe patterns of movements between holdings involved in pyramids;
- Measure the number of movements that would be affected for various scenarios of distance-based derogations;
- Investigate the movements of pigs associated with pyramids to identify trading behaviours that may increase the likelihood of disease spread.

Key findings

Between 2016 and 2018, pig holdings registered to APHA under PRIMO represented 1.3% of the pig holdings that actively moved pigs in Great Britain. Over this period, we identified 19 pyramids within which pigs flow from breeding (Tiers 1 and 2) to finishing (Tier 4) units and that were registered to APHA. We also found 18 production pyramids that only included PRIMO-approved production units (Tier 3) and finishing units (Tier 4) but did not show records of receiving pigs from PRIMO-approved breeding holdings. These production pyramids did not show any records of unique identifier and were therefore considered as not registered (NR) to APHA under PRIMO. Altogether, 516 and 67 holdings were involved in moving pigs within registered and NR pyramids, respectively.

On average, 177,000 non-slaughter pigs moved per week between holdings in GB, among which only 9% moved within pyramids when considering the most inclusive definition of pyramids (Tiers 1 to 4, including NR pyramids). Overall, 21%, 33% and 66% of all non-slaughter pigs moving within pyramids travelled for <10km, <20km and <50km, respectively. In contrast, pigs moving to slaughter from an holding belonging to a pyramid travelled for <10km, <20km and <50km in 3%, 7% and 28% of the time, respectively.

Registered pyramids showed a high level of interconnectivity and were not isolated from the rest of the British pig industry. Notably, pigs were reported moving between 13 of the 19 registered pyramids throughout the study period, forming a large network including 91% of all holdings involved in moving pigs within registered pyramids. Pigs were moving between pyramids through 124 holdings, among which only 35 were found critical for the cohesion of the network.

In the situation where an incursion of an infectious disease occurs and movement restrictions over the all industry are enforced to mitigate its spread, the least restrictive strategy (that is allowing the most number of movements) among all scenarios considered would be based on pyramids being defined as involving holdings from all tiers (Tiers 1 to 4) and included NR pyramids. In this strategy, movement licences would then be

granted for pigs travelling both within pyramids and for <50km of distance. This derogation strategy would allow the flow of ~65% of all pigs within pyramids, particularly preserving movements between Tiers 3 and 4 holdings. Yet, over the total number of pigs moving within GB, this strategy would only allow 6% of the pigs to move, irrespective of the length of time within which movement restrictions are enforced.

Determining which finishing units belonged to the Tier 4 of pyramids was challenging and may introduce some uncertainties in our interpretations. Notably, only 14% of the 1954 non-approved holdings receiving pigs from PRIMO-approved farms met our definition criteria for being included as part of a pyramid. Furthermore, allocating holdings in the Tiers 3 and 4 of specific pyramids using movement records alone was difficult. Efforts to improve registration and database structure should be made if pyramids are to be used for modulating disease control responses.

Policy implications

This study highlights that the structure of the pig industry in GB is more complex than the theoretical top-to-bottom structure of vertically integrated pig production companies. There was a high level of interconnection between pyramids that is misaligned with their use as a basis for compartmentalisation during outbreak response. Furthermore, movement regulations based on pyramids may not be as effective as expected in order to prevent and control the spread of infectious disease or protect the industry as a whole. Efforts to improve registration and database structure are recommended if pyramids are to be used for modulating control responses against outbreaks of pig infectious diseases.

1 Introduction

1.1 Context

In 2013, a disease outbreak scenario exercise, Exercise Walnut, explored responses to a Classical Swine Fever outbreak (APHA 2014). In this exercise, all Great Britain (GB) administrations implemented a Movement Restriction Zone (MRZ) under what was Regulation 24 of the then draft Diseases of Swine Regulations. This meant that all parts of GB outside of Protection Zones or Surveillance Zones were subject to movement restrictions, such that only movements that were both within pyramids and shorter than 10 km were permitted. However, swine industries around the world are often organised in a multi-tiered pyramid structure (Figure 1) where production units owned by the same business can freely, and safely, move pigs between stages of production, from breeding to finishing.

Theoretically, pyramids are organised such that a small number of nucleus herds that produce purebred sows/boars are located at the top of the pyramid and provide animals to multiplier herds. These multiplier farms supply crossbred pigs and replacement gilts to commercial production farms, which in turn raise pigs to be sent to slaughter (Bigras-Poulin 2007; Smith et al. 2013). This top-down pyramid structure is designed to optimise feeding and management procedures, to prevent welfare problems, and be cost-effective. This specialised pyramid relies on the easy flow of large volumes of pigs between these specialised units. This structure is viewed as critical for the pig industry because it is thought that most pig production is directly linked to these pyramids. As such, movement restrictions proposed during Exercise Walnut have the potential to markedly impact the economic viability of the industry, in both the short- and long-term.

In the United Kingdom (UK), a pyramid must be registered formally with the government and approved by Animal and Plant Health Agency (APHA) under article 15 of the Pigs (Records, Identification and Movement) (Scotland) Order 2011 (SSI 2011/327) and equivalent English and Welsh orders (SI 2011/2154, WSI 2011/2830). This order is known by the acronym “PRIMO”. As this provides a legal framework to implement derogations, and because of the findings of Exercise Walnut, EPIC was specifically asked to assess the impacts of implementing MRZs, and particularly to explore how movements within pyramids would be affected by various scenarios of distance-based derogations (EPIC, 2016). This work found that, between January 2012 and December 2013, 12,473,285 pigs were moved within GB from one pig holding to another one, but that only 352,699 of these pigs (3%) were moved within pyramids. We further showed that 56%, 57% and 68% of pigs moving within pyramids traveled less than 10km, 20km and 50km, respectively. A pig from a registered pyramid holding and moving within pyramid was 3.3, 2.04, and 1.24 times more likely to move less than these distances than a pig not registered within a pyramid. Based on this evidence, it was concluded that there was little justification for allowing either 10-km or 20-km movements within pyramids as it posed a disease risk and, because of the small number of movements it would enable, was deemed unlikely to offer adequate and widespread practical benefit to reduce the welfare impact of additional MRZ on the industry and therefore did not offer a cost-effective mitigation.

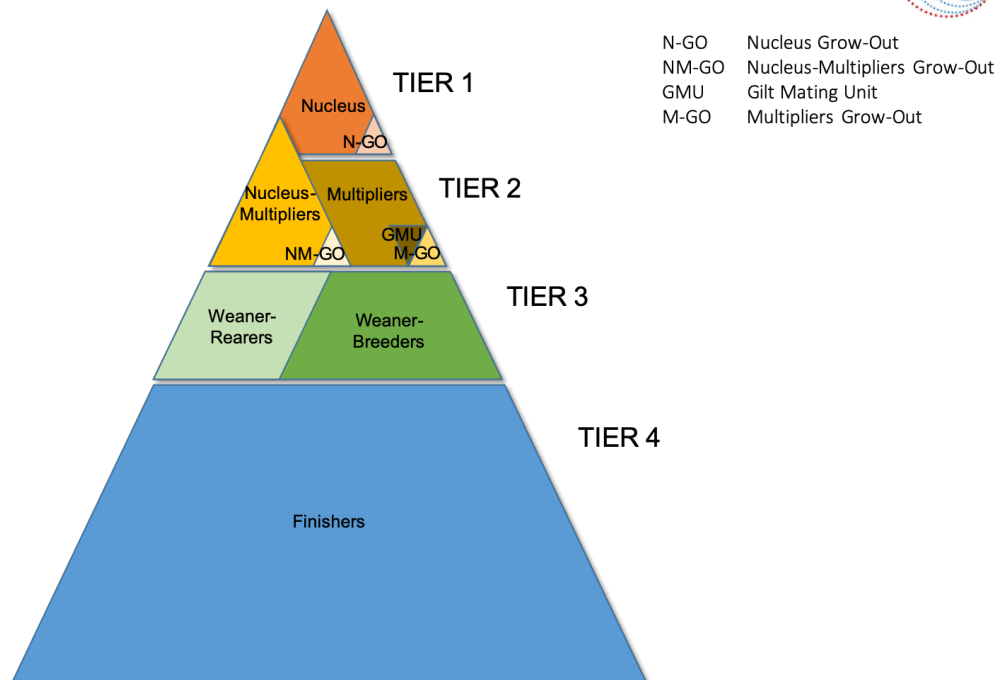


Figure 1: Representation of the pyramid structure as defined by the Animal and Plant Health Agency (APHA)

However, discussions with industry stakeholders highlighted concerns that the definition of ‘*pyramid*’ used when conducting this work was limited to the two upper tiers of holdings that are granted PRIMO status (tiers 1 and 2), thereby ignoring the flow of pigs from breeding (tiers 1 and 2) to weaner-rearers (tier 3) and to finishing farms (tier 4) which represent the majority of movements occurring within pyramids (see Figure 1). In response to the industry concerns regarding such a definition, EPIC was requested by SG to explore how much additional benefit would result if all movements of pigs within production pyramids, *i.e.* from breeding to finishing units, are included in the derogations.

1.2 Objective

The objectives of this work were to:

- Objective i: Characterise pyramids in GB, including the number of farms involved and their geographical distribution, for several definitions of pyramids with increasing inclusiveness;
- Objective ii: Describe patterns of movements between holdings involved in pyramids and explore how these patterns may be impacted by various scenarios of distance-based derogations.
- Objective iii: Measure the number of movements that would be affected for various scenarios of distance-based derogations.
- Objective iv: Investigate the movements of pigs associated with pyramids to identify trading behaviours that may increase the likelihood of disease spread.

2 Material and methods

2.1 Definitions

This work has used several definitions of pyramid. Each definition will provide extended insights of the impact of withholding movements upon each tier of the pyramids, and how the consequent movements will potentially change the epidemiology and consequences of an infectious diseases incursion.

For the purpose of this study, we will only consider holdings being part of a pyramid if (i) they are considered as part of holdings belonging to a registered breeding organisation approved by APHA under PRIMO, thus belonging to the two upper tiers of the production pyramid (named T1 and T2 holdings in this report); (ii) they are holdings defined as either 'Weaner-Rearer' (WR) or 'Weaner-Breeder' (WB) and have been approved by APHA under PRIMO (named T3 holdings); or (iii) they are dedicated finisher units that only receive pigs from 'PRIMO-approved' holdings (i.e. holdings that have been approved by APHA under PRIMO) and exclusively send pigs to slaughter (named T4 holdings). Note that approval procedures carried out by APHA ensure that holdings approved under PRIMO are biosecure operations with strict and regularly reviewed standards related to movements of visitors, vehicles, and stockpersons.

Rather than sourcing pigs from breeding companies in GB, production companies may also enter a business relationship with international breeding companies and will have similar arrangement as those within pyramids. In the movement databases, these production companies would appear as a cluster of one or more T3 holdings, that remain outside any wider pyramid and receive no pigs from British breeding companies (i.e. from T1 and T2 holdings). These T3 holdings may, then, send pigs to dedicated finisher units and form small, but fully integrated, production pyramids that include only T3 and T4 holdings. These small production pyramids represent special cases of pyramid but the absence of connection with neither T1 nor T2 holdings made it difficult to identify them. This constraints led us to classify pyramids into two groups as follow:

- '*Registered pyramids*': pyramids that include at least one T1 and/or T2 holding and have a proper identifier number on the APHA register, known as a 'Nucleus-Multiplier' (NM) number;
- '*Non-registered (NR) pyramids*': pyramids that only include T3 and T4 holdings and are not associated with a registered breeding pyramid (consequently, do not have a proper NM identifier number on the APHA register). Note again, that T3 holdings in NR pyramids are both registered and approved by APHA under PRIMO, and, thus, meet the required standards of biosecurity and animal health.

In this report, different definitions of '*pyramid*' were considered (Figure 2):

- Pyramid definition 1: All holdings belonging to the same registered breeding organisation. Definition 1 therefore implies that only holdings of T1 and T2 would be considered within a given pyramid. This definition is consistent to what was used in the previously reported study (EPIC, 2016).
- Pyramid definition 2: All holdings involved in the downward flow of pigs from a given registered breeding organisation (with an NM number) to any other holding approved by APHA under PRIMO (i.e.

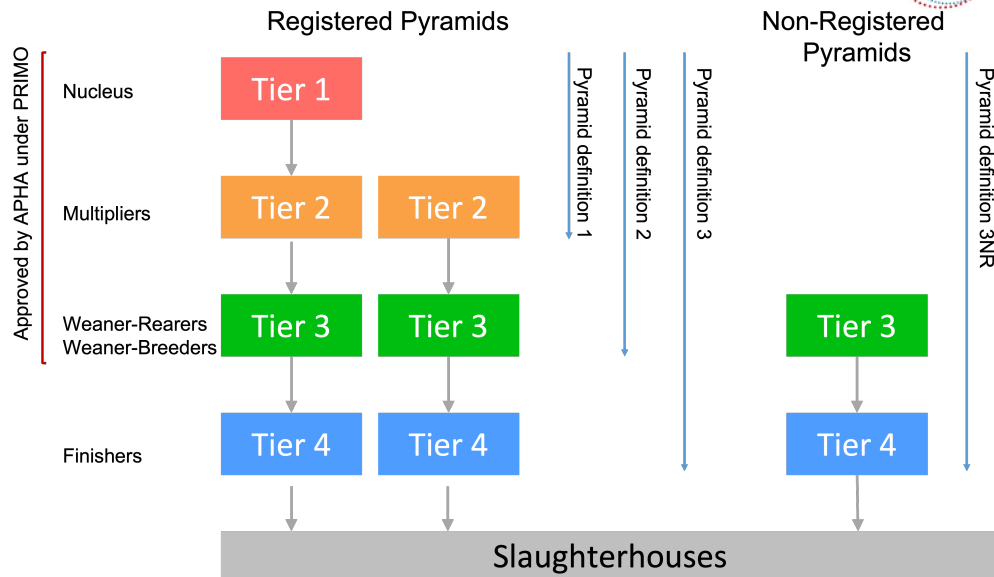


Figure 2: Tiers involved in considered pyramid definitions

T3 holdings). This implies that only T1, T2 and T3 holdings would be considered as part of a given pyramid. Note also that T3 holdings may receive or send pigs from/to holdings belonging to different pyramids.

- Pyramid definition 3: All holdings involved in the downward flow of pigs from a given registered breeding organisation (with an NM number) to any other holdings registered within PRIMO (T1-3) and associated finishing units (i.e. T4 holdings). This implies that T1, T2, T3 and T4 holdings could be considered as part of a given pyramid.
- Pyramid definition 3NR: All holdings involved in a contained downward flow of pigs from breeding to slaughter. This definition is an extension of Definition 3, considering pyramids as either involving all T1, T2, T3 and T4 holdings belonging to registered pyramids or involving those T3 and T4 holdings belonging to non-registered pyramids.

It is worth noting that finishing holdings are subject to conditions for being included in pyramids as T4 holdings. These conditions are defined in section 2.3

2.2 Data management

2.2.1 PRIMO-approved holdings

Three databases were provided to EPIC by APHA. These were:

- Dataset 1: the list of all PRIMO-approved breeding holdings that were registered by each breeding organisation (as provided by the 'Nucleus-Multiplier' sheet) in 2017;

- Dataset 2: the list of all PRIMO-approved weaner-rearer holdings for 2017;
- Dataset 3: the Weaner Breeder Regional Master List for all APHA regions (i.e. Midlands, North, South East, South West, Wales and Scotland) for 2017.

All datasets provide details on the CPH, the name and address and location (i.e. address and postcode) of the holding. Those units registered as approved by APHA under PRIMO, as contained in dataset 1, provided further details on their associated breeding organisations (via a simple NM identifier) as well as the type of production on all of these registered holdings. By combining these datasets, registered holdings were classified according to the tier definitions by their production type. Holdings with production type recorded as either Nucleus or Nucleus Grow Out (N-GO) were categorised as belonging to tier 1 (T1), those with production type recorded as Nucleus-Multiplier (NM), Multiplier, Multiplier-Grow Out (M-GO), Nucleus-Multiplier-Grow Out (NM-GO), Multiplier-Gilt Mating Unit (M-GiltMU), and Nucleus-Multiplier-Gilt Mating Unit (NM-GiltMU) were categorised as belonging to Tier 2 (T2), and those recorded as Weaner-Breeder (WB) and Weaner-Rearer (WR) were categorised as belonging to Tier 3 (T3; Figure 1). The definitions of all broad production types are as follows:

- '*Nucleus*': These are typically closed herds. Nucleus herds produce replacement breeding stock (grandparents) for Multiplier herds and tend to show the highest standards of biosecurity and health status. Pigs that are not selected for breeding go to slaughter.
- '*Multiplier*': These herds breed and multiply replacement breeding stock and, therefore, should be of high standards of biosecurity and health status. Incoming stock are from a named Nucleus herd. The end product is replacement breeding boars and gilts to supply commercial breeding herds. Similar to Nucleus herds, pigs that are not selected for breeding go to slaughter.
- '*Nucleus-Multiplier*': These herds are a combination of both Nucleus and Multiplier herds, thereby two generations of breeding stock are present. These Nucleus-Multiplier herds are 'closed' with high level of biosecurity and health status, with pigs not selected for breeding going to slaughter. Combining two generations reduces the number of movements within the downward chain and therefore creates a lower risk of disease transmission.
- '*Grow-Out*': These herds receive weaner pigs that are selected to be replacement breeding stock and grow them to an appropriate age and weight to be moved onto breeding herds. Grow-Out herds are typically extensions of either a Nucleus, a Nucleus-Multiplier, or a Multiplier herd and, therefore, have the same requirements in term of biosecurity standards and health status as their source farms.
- '*Gilt Mating Unit*': These are herds where young gilts (normally from a Multiplier herd or an associated Grow-Out herd) are reared and then mated. Pregnant gilts are then sent to Weaner-Breeders (often outdoor breeding herds) to avoid mating taking place at the destination.
- '*Weaner-Breeder*': These herds breed parent stock to produce weaned piglets that will be sold directly or move to rearing and/or finishing herds. Farrowing (and mating, unless gilts supplied in-pig from a gilt-mating unit) and rearing generally take place on site and incoming animals are usually from Nucleus or Multiplier herds to obtain replacement stock.

- '*Weaner-Rearer*': No breeding takes place in these herds. Incoming stock are weaned piglets (7 to 10kg) from weaner-breeder herds and are simply grown on to the next stage (30 to 35kg) at which point the pigs are moved to finisher premises. Rearing herds can be run on a continuous, or an all in/all out batch system. Continuous systems receive small piglets and move larger pigs off each week.
- '*Finisher*': No breeding takes place in these herds. Incoming stock are weaned piglets (7 to 10kg) from breeding herds (Nucleus, Multiplier or Weaner-Breeders) or grown piglets of 30 to 35kg from weaner-rearer herds. In these premises, pigs are fed to bring them to a liveweight of >70 kg and send to be slaughtered in abattoir.

Among all PRIMO-approved holdings defined as T1 or T2, one holding did not show a registered record of pyramid membership. While this missing information indicates that the PRIMO Dataset 1 is not 100% complete nor accurate, the movement pattern of this holding as well as its holding ID number provided by APHA indicated that it was a member of the Pyramid #6. Missing information was therefore amended accordingly.

2.2.2 Pig movements

All records of movements of pigs for the period January 2016 to December 2018 were extracted from the Scottish livestock electronic identification and traceability database (ScotEID) and the electronic Animal Movement Licensing System (eAML2). The ScotEID and eAML2 databases both provide a comprehensive picture of all movements of pigs in GB at batch rather than individual pig level. Each movement record reports the CPH of departures and destination, the postcode and addresses for departure and destination, the number of animals involved, and the date of the movement. This information provided the basis to list all unique premises, whether pig holdings or gathering places, that were actively involved in moving pigs in GB (APHA 2019; Smith et al. 2020).

Additional details of movements are recorded in eAML2, providing information on the purpose of each movement (e.g. "Farm to Slaughter Movements", "Market to Destination(S) Movement Scope"), and indicated whether the movement is considered under PRIMO. This information, together with the addresses provided, allowed slaughterhouses, markets, show-grounds, and ferry collection centres to be differentiated from agricultural holdings.

An extensive data cleaning procedure was then carried out to ensure pig holdings were unique and that no duplications remained in the dataset after both ScotEID and eAML2 datasets were integrated. The procedure consisted of successive steps identifying duplicated, erroneous, and missing records for holdings' CPH identifier and spatial location. Details of spatial location for all holdings involved in the trade of pigs during the study period were extracted either from provided postcodes or by linking to the 2013 pig keeper register. When possible, postcode from the unit was considered rather than postcode of the main office. The location of all premises with unknown spatial location, either because of missing or erroneous postcode records, were extrapolated from the country and parish information of their CPH number.

2.2.3 Holding type

Because EPIC did not have up-to-date information on holdings that belong to a quality assurance scheme, we defined criteria to differentiate commercial holdings from smallholders based on the total number of pigs that moved in (n_{in}) and out (n_{out}) between January 2016 and December 2018. We assumed that smallholders will move fewer pigs than a given threshold θ , such that $\max(n_{in}, n_{out}) < \theta$. This threshold θ was calculated over all records of pig movements in GB and determined as the inflection point in the cumulative distribution of holdings as a function of total number of pigs received or sent over the study period.

2.3 Pyramid construction

In this report, a given individual pyramid p is described by the list of holdings present in each tier such as $p = [T_1, T_2, T_3, T_4]$, where each element T_1, T_2, T_3 and T_4 are lists of all associated T1, T2, T3 and T4 holdings, respectively. In this situation, the lists of holdings in T_1 and T_2 for a given pyramids p are given by the data recorded in Dataset 1. Concomitantly, holdings listed in T_3 and T_4 are identified by records in Dataset 2 and Dataset 3 (i.e. informing on the approval status of holdings), as well as the flow of pigs departing from T1 and/or T2 holdings. Figure 3 illustrates how holdings are allocated to pyramids.

First, we considered that T_3 lists all T3 holdings receiving pigs from holdings involved in T_1 and T_2 only. In that way, we ignore all T3 holdings (as identified in Datasets 2 and 3) that participate to upward movements to any holdings in T_1 or T_2 . By doing so, we considered that T1/T2 holdings would rarely receive replacement gilts from T3 holdings belonging to the same pyramid.

We further considered that all holdings receiving pigs from any holdings listed in T_1, T_2 or T_3 are eligible to be included in T_4 . Upon the list of candidate holdings, multiple criteria were implemented to select or reject holdings for inclusion in T_4 (Figure 3). Here, a T4 holding will be selected among all candidate pig holdings if:

- they exclusively send pigs to slaughter, either directly to slaughterhouse or through market;
- they exclusively receive pigs from PRIMO-approved holdings;
- they had no movements from/to a showground recorded during the study period.

In reality, pigs coming from outside GB can be imported into pyramids with assurance that the provenance of these animals are from holdings with equivalent biosecurity and animal health standards. Under veterinary risk assessments, these animals can be introduced into any holdings or any tiers of a given pyramid. As a consequence, non-approved holdings showing records of movements from outside GB (i.e. through ferry ports) remained eligible to be included in T_4 . Similarly, all records of movements for the purpose of disease surveillance and/or animal health (i.e. to APHA or SRUC veterinary surveillance centres or to veterinary clinics) did not affect the eligibility of non-approved holdings into T_4 .

As mentioned previously, one or more T3 holdings may remain completely independent of breeding companies, whether forming small production pyramids that include only T3 and T4 holdings (i.e. NR

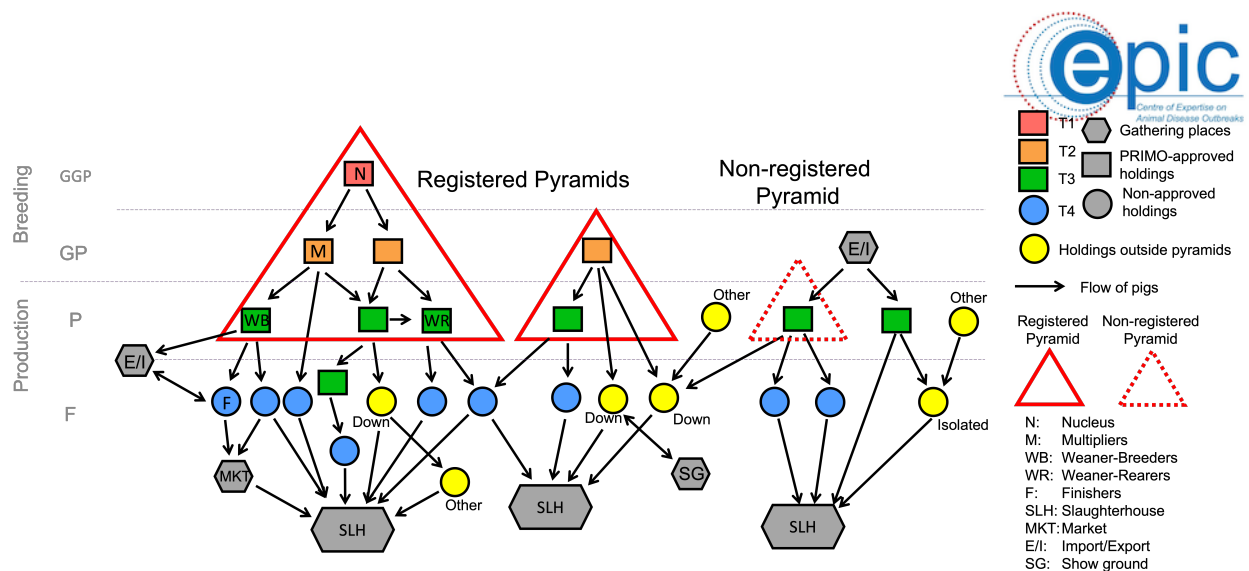


Figure 3: Schema illustrating criteria defining T4 holdings. Here, T4 holdings are chosen among pig holdings that trade pigs with PRIMO-approved holdings and as a function of the recorded movement patterns. All yellow solid circles indicate pig holdings that are *not* considered as T4 holdings. Inspired from discussion and material from Mark Rigby (APHA).

pyramids) or trading with other holdings whose trading behaviours prevent them from being defined as T4 holding (Figure 3). These represent special cases where both T_1 and T_2 are empty. To identify NR pyramids, we first assumed that they would form unique cluster of holdings (also named network 'component') that are connected to each other but isolated from the rest of the industry. Then, we constructed the network formed by the movements of pigs between the T3 and T4 holdings that were left out from any given p . Based on this network, we considered all components as NR pyramids.

2.4 Descriptive analyses

A descriptive analysis was first carried out, describing the spatial distribution of pyramids (either registered or non-registered) in GB and exploring the network of pig movements in GB with regards to pyramidal structures (i.e. Tiers 1, 2, 3 and 4) over the period of interest, i.e. the time period between the 1st of January 2016 and the 31st of December 2018. The analyses considered all movements between pig holdings that were approved by APHA under PRIMO and/or were involved in pyramids. All geographical distances between premises correspond to Euclidian distances, expressed in kilometres, and calculated using Pythagoras' theorem.

Next, the consequences of the implementation of movement restrictions for the British swine industry were investigated. To evaluate the volume of movements that would be prevented from moving if the MRZ was imposed and if distance-based derogations for movements occurring within pyramids would be beneficial, we explored the number of pigs moving as a function of the distance travelled and the considered pyramid definition. In particular, we look at the impact on the number of pigs that would be prevented from moving and on the structure of the pig movements network under the hypothesis that movements would be allowed

if they were both made within pyramids and for distances smaller than either 10km, 20km or 50km.

The impact of uncertainties of two key temporal parameters was then explored: the time of incursion and the duration of the epidemic. To account for the influence of the time of incursion, we considered that incursion would occur every Monday of the study period and that movement restrictions would be enforced for a period Δt , a proxy for the duration of a given outbreak. As such, $1095 / \Delta t$ consecutive independent snapshots of the network of movements. These snapshots enable the exploration of the influence of the duration of the epidemics on the number of pigs that would be potentially unable to move from farms at the correct point in the production cycle. Here, we considered that Δt would vary from one week to 26 weeks (six months), providing information relevant for disease control activities.

While there is no control of movements departing from pyramids, movements of pigs to other holdings outside pyramids are possible, provided the holdings then undergo standstill. In accordance with PRIMO, pig holdings outside pyramids are required to keep pigs on farm for a compulsory minimum of 20 days prior to any non-slaughter movements to reduce the risk of uncontrolled spread of infectious disease. In contrast, holdings within registered pyramids are subject to a derogation which allows the movement of pigs on and off the premises within this 20-day standstill period. In this report, we investigated how the distribution of standstill duration varied between holdings involved within pyramids and those outside pyramids. These latter were categorised into three groups (Figure 3): (i) those that received pigs from pyramids but did not meet criteria for being included as T4 holding ('Down'), (ii) those that received pigs from T3 holdings that were not involved in pyramids (either registered or not) and therefore did not meet criteria for being included as T4 holdings ('Isolated'), and (iii) all holdings that did not trade pigs with pyramids ('Others').

3 Results

3.1 General description of the British pig industry

Overall, 31,550 holdings and 262 gathering premises were actively participating in moving pigs or were registered within GB as PRIMO-approved between January 2016 and December 2018. Among these 31,550 holdings, 2334 were located in Scotland, 24,953 were located in England and 4486 in Wales. The remaining 2 holdings showed a postcode from Northern Ireland and, unlike movements reported as import or export, did not provide records of port of entry. Figure 4 shows the spatial distribution of all active pig holdings in GB during the study period.

Table 1 shows the number of holdings registered in the APHA database in 2017 stratified by facility type as reported in the APHA register. Briefly, 104 holdings were registered as either T1 or T2 holdings. In addition, 275 holdings were registered as T3 holdings, including 25 WR holdings, 236 WB holdings, and 14 holdings registered as both WB and WR holdings. Altogether, WB and WR holdings represent 73% of all holdings approved by APHA under PRIMO. When linking the list of all PRIMO-approved holdings with the movement dataset, 18 holdings with unique CPH showed multiple postcodes. We considered that holdings with multiple

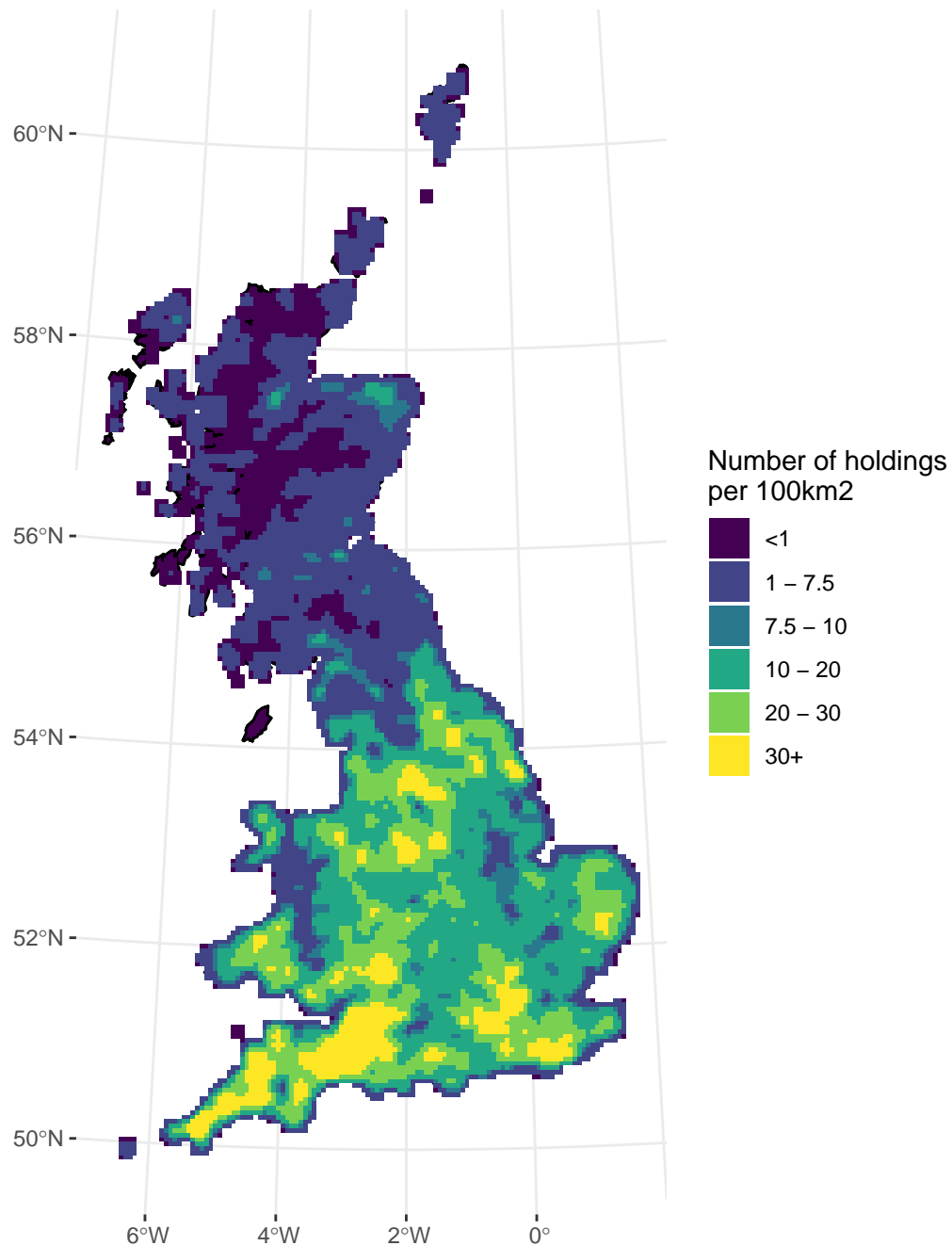


Figure 4: Estimated pig holding density in Great Britain during the study period. Here, the holding density was computed over a grid of 5km-wide squared cells using the kernel density function, creating a smoothed density surface. For its computation, we further considered a search radius (or bandwidth) of 15km, similar to previously generated maps (APHA, 2019).

Table 1: Distribution of PRIMO-approved holdings per type.

Production type	Tier	Number of holdings	Proportion of registered holdings
N-GO	1	9	2.4%
Nucleus	1	13	3.4%
undefined	1 or 2	15	4%
M-GO	2	18	4.7%
M-GO-GiltMU	2	1	0.26%
Multiplier	2	23	6.1%
NM-GiltMU	2	1	0.26%
NM-GO	2	5	1.3%
Nucleus Multiplier	2	19	5%
WB	3	236	62%
WB-WR	3	14	3.7%
WR	3	25	6.6%

Note:

N: Nucleus unit; M: Multiplier unit; NM: Nucleus Multiplier unit; WR: Weaner-rearer unit; WB: Weaner-breeder unit; GO: Grow-out unit; GiltMU: Gilt Mating Unit. While WB-WR holdings are farms present in both the weaner-rearer and the weaner-breeder register, 'Undefined' holdings are grow-out and gilt mating units from undefined tier (either Tier 1 or Tier 2).

postcodes could indicate either postcodes were erroneously recorded (and could not be corrected during the data cleaning procedures) or have multiple units within a 5-mile radius area. Because it was impossible to distinct those two hypothesis, and in order to be as conservative as possible, all units sharing CPH numbers were considered separately but were all approved by APHA under PRIMO. The final dataset of PRIMO-approved pig holdings therefore included 400 units, including 109 T1/T2 holdings and 291 T3 holdings. Among these T3 holdings, 251 were recorded as WB holdings, 26 were recorded WR holdings and 14 were recorded as both WB and WR holdings. These 400 holdings represent 1.27% of the 31,550 pig holdings recorded as moving pigs during the study period.

In total, 579,407 movements were recorded during the study period, averaging 193,136 movements per year and 48,284 movements per month. Overall, 54,782,445 pigs were moved in GB during the study period, including 25,834,734 pigs directly sent to slaughter (47.2%).

Figure 5 shows the number of daily movements of pigs during the study period, highlighting an overall lack of seasonality in the number of pig movements, irrespective of the movements involving at least one PRIMO-approved holding (i.e. T1, T2 and T3 holdings). Over the 579,407 movements that were recorded in

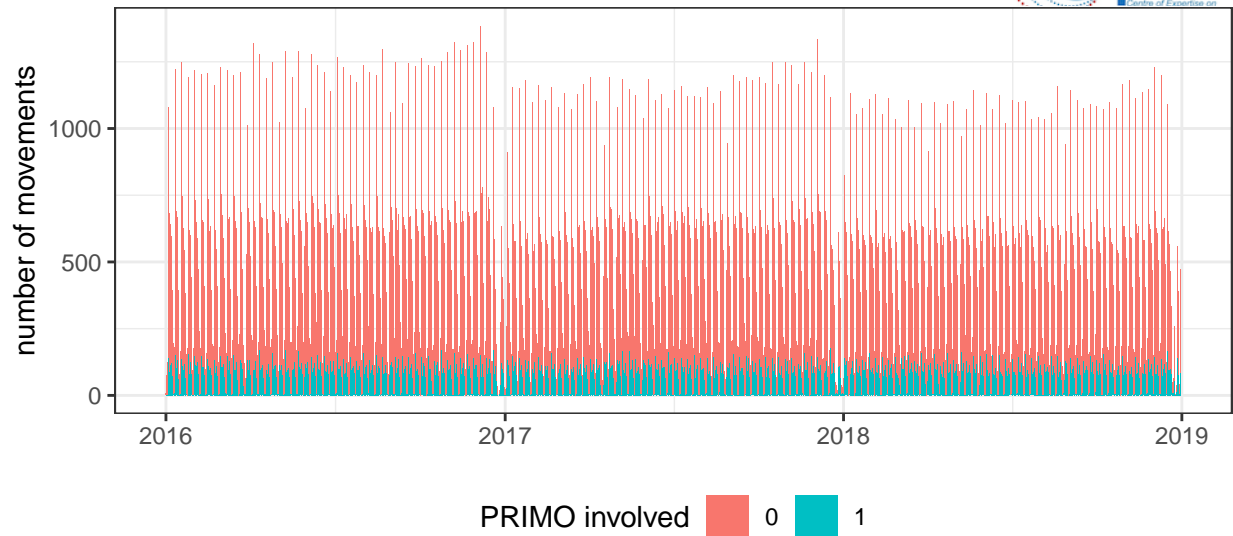


Figure 5: Number of daily movements of pigs. Here, blue bars indicate the number of daily movements involving at least one PRIMO-approved holding (T1, T2 and T3 holdings) and red bars indicate the number of those that did not involve at least one PRIMO-approved holding.

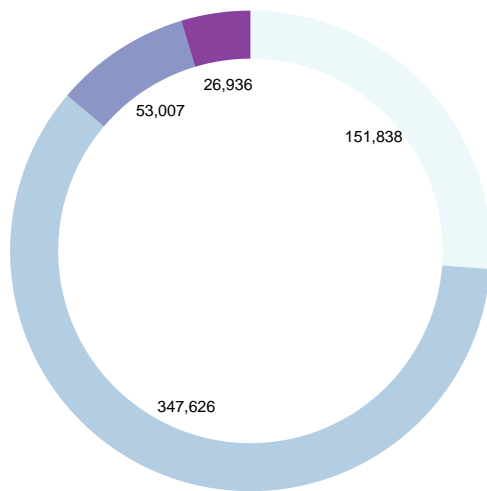
GB during the study period, 374,562 (64.6%) movements directly went to slaughter (Figure 6) and 26,936 (4.6%) departed from PRIMO-approved holdings.

During the study period, 79,943 movements, or 13.8% of the total number of movements recorded (i.e. slaughter and non-slaughter movements), involved at least one PRIMO-approved holding (Figure 6). This represents 26,648 movements per year and 2,221 per months. Movements involving at least one PRIMO-approved holding involved 17,325,647 pigs, which represented 31.6% of the total number of pigs (i.e. slaughter and non-slaughter pigs) moved during the study period. This represents 5,775,216 movements per year and 481,268 per months.

Among all movements (i.e. slaughter and non-slaughter) involving at least one PRIMO-approved holding, 26,538 (33.2%) movements departed from T1 or T2 holdings and 51,613 (64.6%) movements departed from T3 holdings. Details of the destination and number of pigs involved is shown in Table 2. Among the 26,538 movements that departed from T1 or T2 holdings, 3245 (12.2%) were sent to another top tier holding, 5684 (21.4%) were sent to a T3 holding, 7336 (27.6%) were sent directly to slaughter, and 9120 (34.4%) were sent to an holding not registered as either T1, T2 or T3 holding. In contrast, among the 51,613 movements departing from T3 holdings, 19,600 (38%) were sent directly to slaughter, 4619 (8.9%) were sent to another T3 holding, and 22434 (43.5%) were sent to a holding not registered as either a T1, T2 or T3 holding (Table 2). Note that these latter, together with those receiving pigs from T1/T2 holdings, represent candidates for T4 holdings.

While most movements involving PRIMO-approved holdings were movements down the production chain

Batches



Pigs (million)

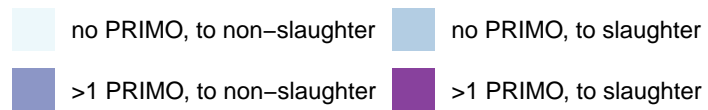
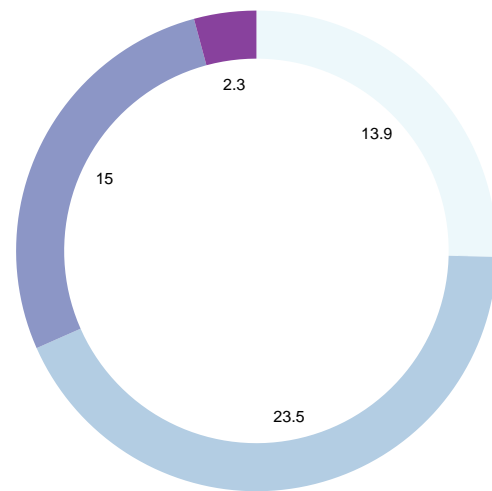


Figure 6: Importance of PRIMO-approved holdings in movement database. Proportion and number of slaughter and non-slaughter pigs and batches of pigs moving in GB between at least one PRIMO-approved holdings.

(i.e. from the upper tiers of pyramids to slaughter), 1761 (2.2%) movements were recorded moving up pyramids, with 1422 movements departing from a non-approved holding to T3 holdings and 293 to holdings of the upper tiers (Table 2). In total, this represent 308,360 pigs over the study period, mainly moving toward T3 holdings (Table 2).

Over the study period, 166 import events from Northern Ireland or from other European countries were recorded, representing a frequency of imports of almost once a week ($n = 1.06$) for a total number of 311 incoming pigs per week. Among these, 60 (36.1%) batches went through a Scottish port but only 3 (1.8%) were destined to a Scottish holding. Overall, most (87.4%) pigs that were imported went through a Scottish port but only 18 pigs stayed in Scotland over the study period.

Among these 166 import events, only 76 (45.8%) import events had a PRIMO-approved holding as destination, with 25 (32.9%) import events sent to holdings of the upper tiers and 51 (67.1%) import events sent to T3 holdings. This represented a frequency of imports of almost twice a month ($n = 2.11$).

3.2 Identification of T4 holdings

Table 2: Total number of batches and pigs that moved between departure and destination types during the study period.

Departure	Destination						Batches		Pigs	
	Gathering			Pyramid			n	%	n	%
	Slaughter	Market	Export	Tiers 1 and 2	Tier 3	Tier 4				
Live animals										
Tiers 1 and 2	-	-	-	-	-	-	7,153	1.23%	973,681	1.78%
Tiers 1 and 2	-	-	-	-	-	Yes	2,032	0.351%	350,332	0.639%
Tiers 1 and 2	-	-	-	-	Yes	-	5,684	0.981%	307,574	0.561%
Tiers 1 and 2	-	-	-	Yes	-	-	3,245	0.56%	660,926	1.21%
Tiers 1 and 2	-	-	Yes	-	-	-	97	0.0167%	6,742	0.0123%
Tiers 1 and 2	-	Yes	-	-	-	-	991	0.171%	28,098	0.0513%
Tier 3	-	-	-	-	-	-	18,698	3.23%	9,481,851	17.3%
Tier 3	-	-	-	-	-	Yes	3,833	0.662%	1,169,019	2.13%
Tier 3	-	-	-	-	Yes	-	4,619	0.797%	1,585,473	2.89%
Tier 3	-	-	-	Yes	-	-	45	<0.01%	11,468	0.0209%
Tier 3	-	Yes	-	-	-	-	4,818	0.832%	114,237	0.209%
Tier 4	-	-	-	-	-	-	9	<0.01%	34	<0.01%
Tier 4	-	-	-	Yes	-	-	1	<0.01%	27	<0.01%
Tier 4	-	-	Yes	-	-	-	1	<0.01%	34	<0.01%
Tier 4	-	Yes	-	-	-	-	2,141	0.37%	32,042	0.0585%
outside pyramid	-	-	-	-	-	-	109,334	18.9%	13,246,682	24.2%
outside pyramid	-	-	-	-	Yes	-	1,422	0.245%	246,286	0.45%
outside pyramid	-	-	-	Yes	-	-	293	0.0506%	50,579	0.0923%
outside pyramid	-	-	Yes	-	-	-	48	<0.01%	528	<0.01%
outside pyramid	-	Yes	-	-	-	-	40,215	6.94%	633,534	1.16%
Market	-	-	-	-	-	-	14,713	2.54%	148,374	0.271%
Market	-	Yes	-	-	-	-	1	<0.01%	1	<0.01%
Imports	-	-	-	-	-	-	90	0.0155%	3,069	<0.01%
Imports	-	-	-	-	Yes	-	51	<0.01%	42,867	0.0782%
Imports	-	-	-	Yes	-	-	25	<0.01%	2,628	<0.01%
Slaughter animals										
Tiers 1 and 2	Yes	-	-	-	-	-	7,336	1.27%	660,333	1.21%
Tier 3	Yes	-	-	-	-	-	19,598	3.38%	1,633,499	2.98%
Tier 3	Yes	-	Yes	-	-	-	2	<0.01%	27	<0.01%
Tier 4	Yes	-	-	-	-	-	25,610	4.42%	2,363,747	4.31%
outside pyramid	Yes	-	-	-	-	-	322,014	55.6%	21,177,122	38.7%
outside pyramid	Yes	-	Yes	-	-	-	2	<0.01%	6	<0.01%
Market	Yes	-	-	-	-	-	17,390	3%	573,358	1.05%

Note:

n: total number of batches/pigs recorded during the study period; %: proportion of batches/pigs over all movements departing from given departure types

The number of batches/pigs leaving each type of departure but not indicating any type of destination inform on the volume of movements to farms outside the pyramids.

From January 2016 to December 2018, 9,120 (11.4%) and 22,434 (28.1%) movements from T1 and T2, and T3 holdings respectively, were sent to non-approved pig holdings. Overall, 1954 unique holdings received pigs from PRIMO-approved holdings, among which 811 sent pigs exclusively to slaughterhouses, exports (by ferry), and to surveillance centres or veterinary institutes. Among these 811 holdings, 269 (33.2%) only received pigs from PRIMO-approved holdings, imports (by ferry), and from veterinarians or veterinary institutes. Therefore, these latter premises can be defined as T4 holdings.

Figure 7 shows the distribution of the total number of batches and pigs that were received and sent by the 269 potential T4 holdings during the study period. These distributions are clearly bimodal, with holdings mainly moving ~10 pigs or ~10,000 pigs during the study period. This seems to indicate that PRIMO-approved holdings may still trade pigs with smallholders. Figure 8 shows the movement behaviour of the 269 potential T4 holdings in term of batches received and sent (Figure 8A) and, similarly, in term of pigs received and sent (Figure 8B) during the study period. While no clear patterns can be observed in Figure 8A, Figure 8B clearly outlines the production type of these holdings: (i) finishing and weaning-to-finishing holdings, located along the diagonal line, send a similar number of pigs sent to slaughter to the number they received, (ii) breeding-to-finishing holdings, located parallel to the y-axis, send a markedly larger number of pigs to slaughter than the number they received, and (iii) smallholders, showing few pigs moving both in and out during the study period.

To distinguish smallholders from commercial holdings within these 269 potential T4 holdings, smallholders were defined as both receiving and sending a number of pigs below a given threshold. A large number of possible threshold values was considered across all pig holdings in GB. In this work, we selected the threshold θ value at which the proportion of commercial holdings is optimised (as indicated by the dotted vertical line in Figure 9). This process indicated that 26,277 holdings (i.e. 83.2% of the total number of pig holdings in GB) were receiving and sending less than 76 pigs during the study period (i.e. about 25 pigs annually), and could be defined as smallholders. When this threshold was applied to the list of potential T4 holdings, 64 pig holdings could be characterised as smallholders. Although these should not be considered as T4 holdings, we however acknowledge that separating small holdings from commercial producers in such a way may be somewhat artificial and could bias the inference of our analysis. For the purpose of this study, we therefore included all holdings identified as T4 holdings, irrespective of whether they are defined smallholders or not.

When reporting movements of pigs into the electronic database (eAML2), pig holders in England and Wales have the opportunity to declare movements as made under PRIMO. Declaring movements as made under PRIMO implies that both the departure and destination holdings are involved in pyramids recognised by APHA under PRIMO, and thus should be either T1, T2, T3 or T4 holdings. To check if this data can be used to efficiently list T4 holdings in England and Wales, we cross-checked our list of 261 T4 holdings from England and Wales with the list of non-approved holdings involved in PRIMO movements as recorded in eAML2. This revealed that only 3.49% of the 3437 non-approved holdings involved in movements declared as made under PRIMO met our criteria to be defined as T4 holdings. For comparison, 277 over the 356 PRIMO-approved holdings (77.8%) registered in England and Wales reported PRIMO movements in the eAML2 movement

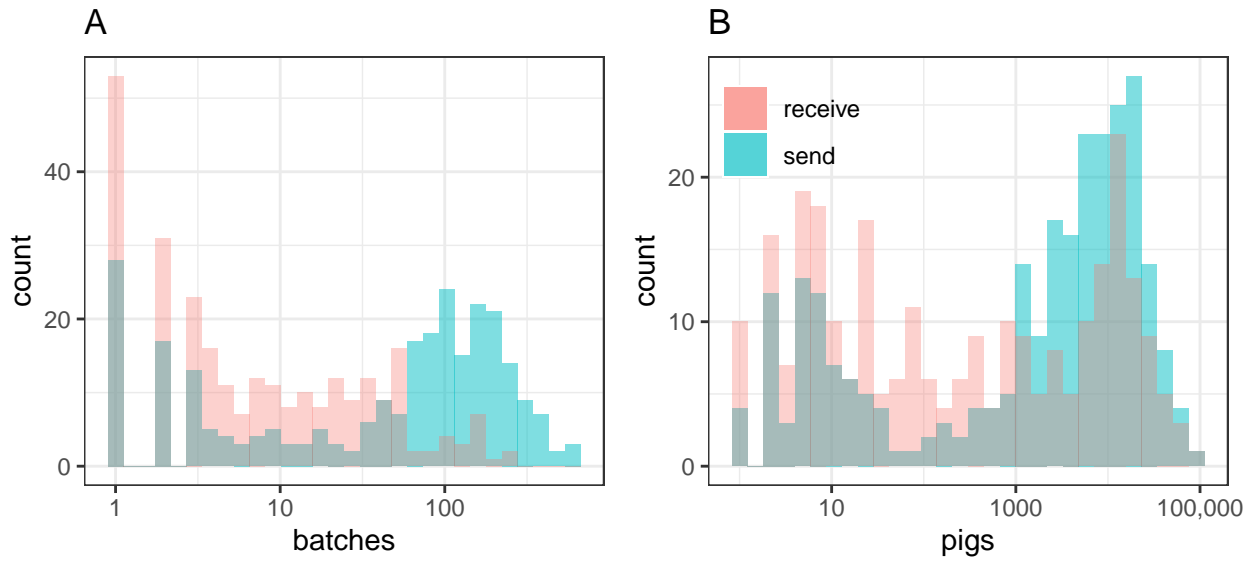


Figure 7: Distribution of the number of batches and pigs that were traded by potential T4 holdings. Please note, the x-axis is on the log-scale. Note also that grey bars indicate the overlap between the two distributions.

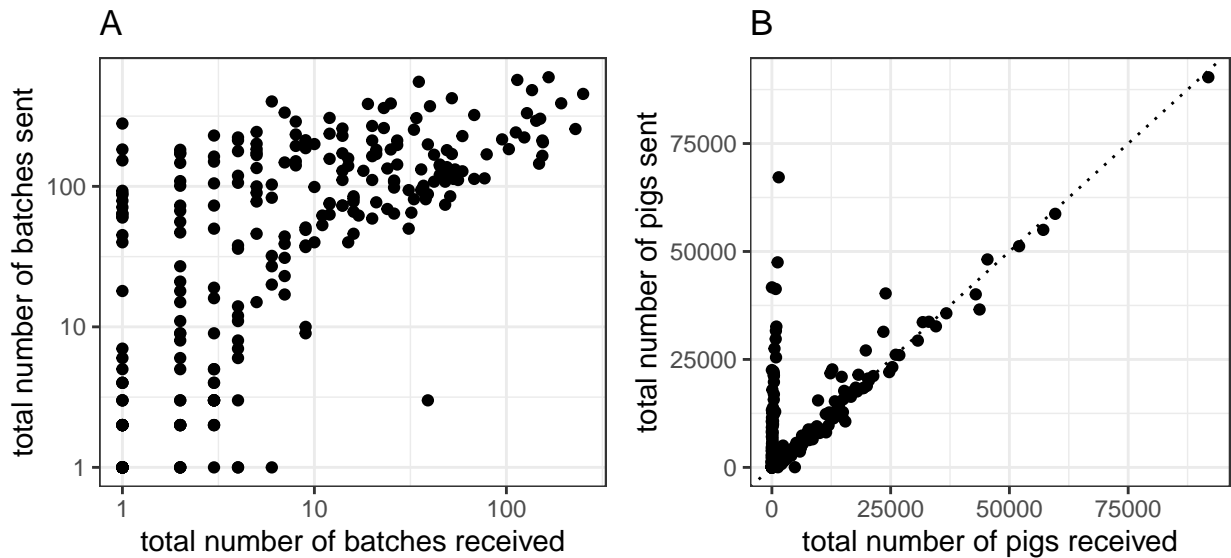


Figure 8: Movement behaviour for potential T4 holdings

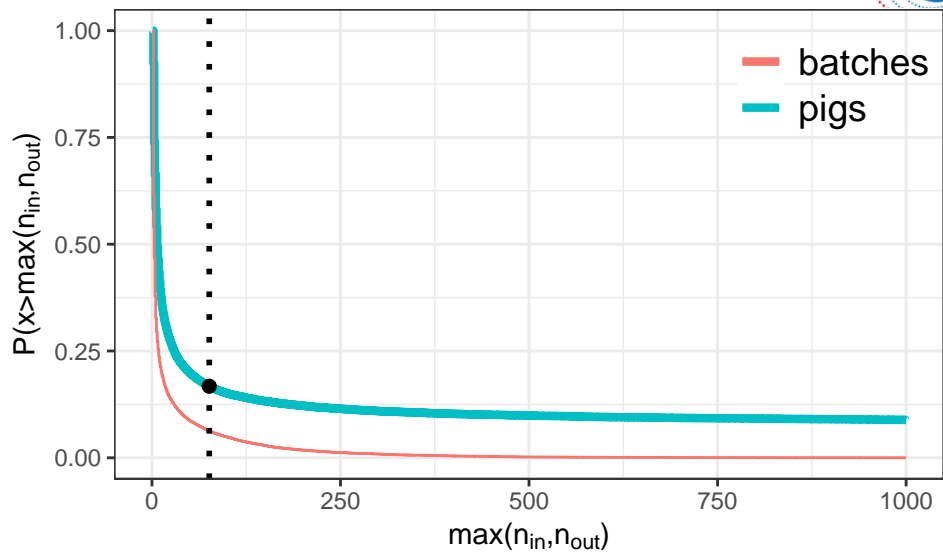


Figure 9: Identification of small holdings. Here, we assumed that smallholders will move less pigs than a given threshold. This threshold was calculated over all records of pig movements in GB and determined as the inflexion point (solid black dot) in the cumulative distribution of holdings as a function of total number of pigs received or sent over the study period.

database.

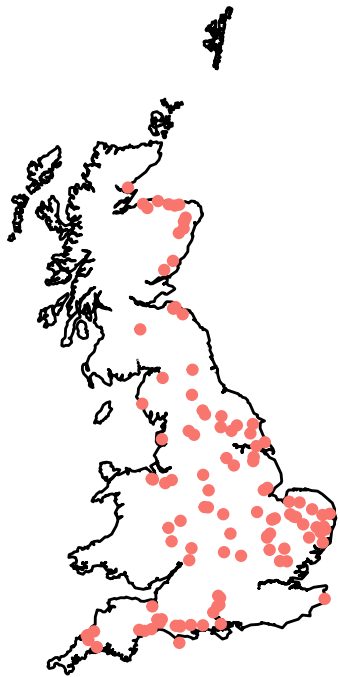
Detailed flow of slaughter and non-slaughter pigs from holdings of all tiers is shown in Table 2. The spatial distribution of all holdings involved in pig production pyramids, structured by their tiers, is shown in Figure 10.

3.3 Description of the registered pyramids

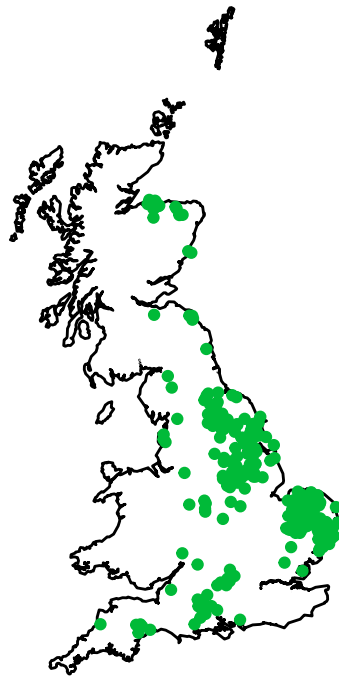
3.3.1 General characteristics

During the period January 2016 to December 2018, 19 pyramids were registered to APHA and moved pigs from breeding (i.e. from T1 and T2 holdings) to slaughter. While all registered pyramids involved at least one holding from the top tiers, their number varied markedly between pyramids. In GB, 5 (26.3%) pyramids include single holdings from the two top tiers, while 3 (15.8%) showed more than 10 holdings from the two top tiers. Together, these 3 large pyramids involved 67 T1/T2 holdings, which represented 61.5% of all holdings registered in Tier 1 and Tier 2. Descriptive statistics of the number of T1 and T2 holdings involved in each registered pyramid are given in Table 3.

Tier 1 and Tier 2



Tier 3



Tier 4

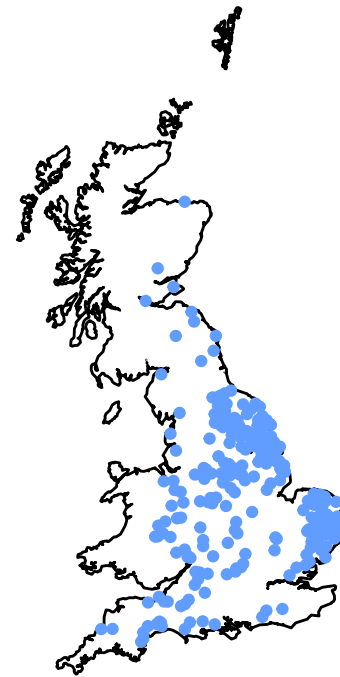


Figure 10: Spatial distribution of all holdings involved in pyramids in GB structured by tier. Note that all locations were randomly jittered within 10km to ensure confidentiality of farm locations.

Table 3: Number of holdings in Tiers 1 and 2 per registered pyramid.

Size category	Number of registered pyramids	Number of holdings involved			
		N	Mean	Median	Range
(0,1]	5	5	1.000000	1	1 - 1
(1,5]	9	25	2.777778	3	2 - 5
(5,10]	2	12	6.000000	6	6 - 6
(10,30]	3	67	22.333333	22	18 - 27

While all registered pyramids showed records of movements during the study period, 5 T1/T2 holdings from 4 pyramids did not show records of movements during the study period and may be inactive during the study period. Considering the most inclusive definition for pyramids involving only registered pyramids (i.e. *Pyramid definition 3*), pyramids included between one and 183 holdings in GB (Table 4). The largest pyramid (Pyramid #6) included 27 T1/T2 holdings, 69 T3 holdings and 87 T4 holdings. For comparison, registered pyramids would, on average, involve 6 T1/T2 holdings, 13 T3 holdings, and 15 T4 holdings. Figure 11 shows the spatial location of all holdings involved in each individual pyramid registered in 2017.

Among the 19 active pyramids, a single pyramid was fully located in Scotland but involved only one holding exclusively sending pigs to a slaughterhouse. On the other hand, 4 registered pyramids have some T1/T2 holdings in Scotland whereas 3 have some Scottish T3 holdings. In total, 5 registered pyramids were partly located in Scotland (Figure 12). Similarly, 4 pyramids were partly located in Wales, with only one (1) registered pyramid involving Welsh top tier holdings and no (0) registered pyramid involving Welsh T3 holdings. Overall, 41 Scottish holdings were found to be involved in at least one production pyramid, including 19 T1/T2 holdings, 16 T3 holdings and 6 T4 holdings. The remaining 486 holdings, were mostly (98.1%) located in England.

Considering *Pyramid definition 3*, the median distance between holdings in each registered pyramid with at least 3 holdings ranges from 5.2 km to 200 km. In contrast, the median distance between farms is markedly greater when considering only T1/T2 holdings (i.e. *Pyramid definition 1*) (Figure 13).

Figure 14 compares the geographical extent of each registered pyramid in GB as a function of the definition of a pyramid. When looking at pyramids spread over multiple countries, a difference in spatial extent can be observed. Again, considering *Pyramid definition 3*, pyramids with holdings located in more than one country (whether including Scotland and/or Wales) showed the widest spatial extent, with median distances between holdings of the same pyramid averaging around 190 km (min-max: 179 km – 201 km). In contrast, pyramids with holdings located in a single country showed a consequent smaller spatial extent, with median distances averaging around 43.9 km (min-max: 5.19 km – 201 km).

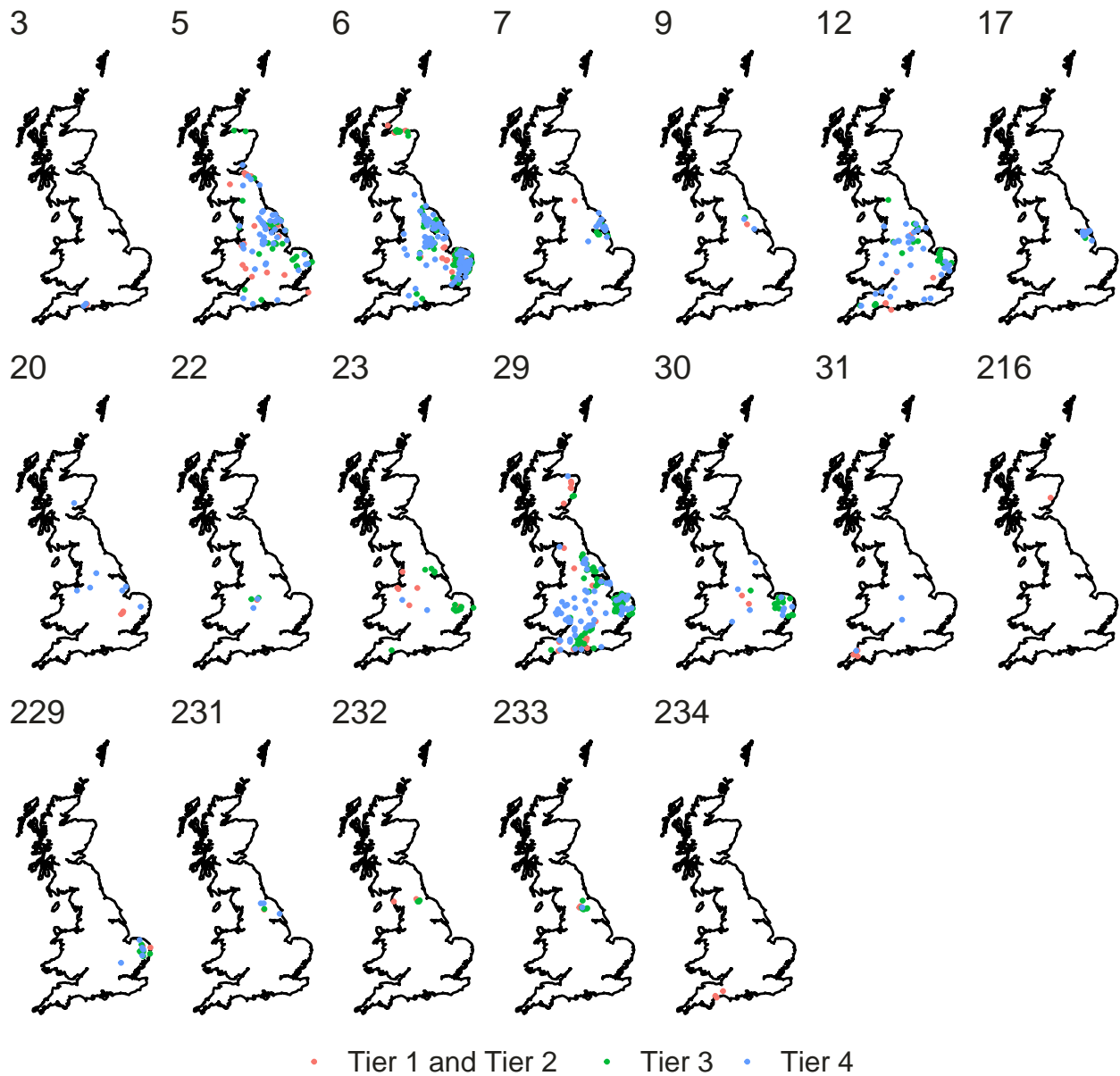


Figure 11: Map showing the location of all holdings with a proper spatial location for each production pyramid in Great Britain. Number at the top of each map indicates the pyramid identifier. The colour of each point represents the Tier of each holding. Note that all locations were randomly jittered within 10km to ensure confidentiality of farm locations.

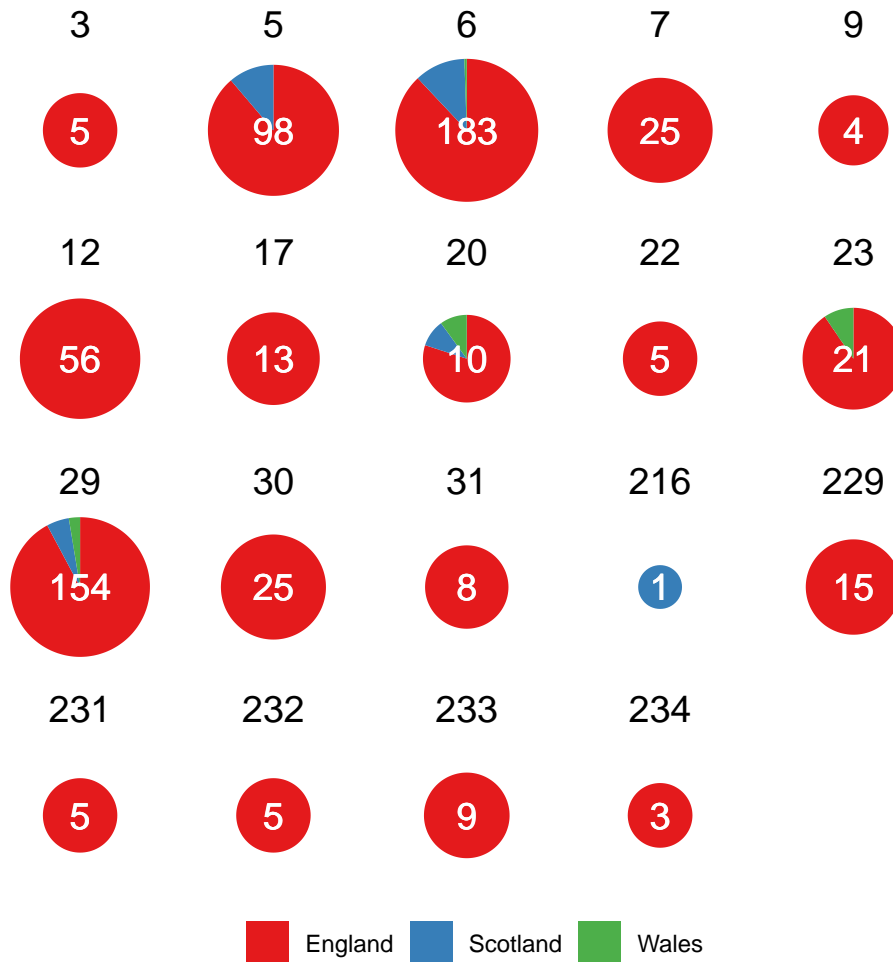


Figure 12: Pie chart showing the proportion of Scottish, Welsh and English holdings in registered pig pyramids. Number at the top of each pie chart indicates the pyramid identifier, while the size and number at the centre represent the total number of holdings involved in each pyramid.

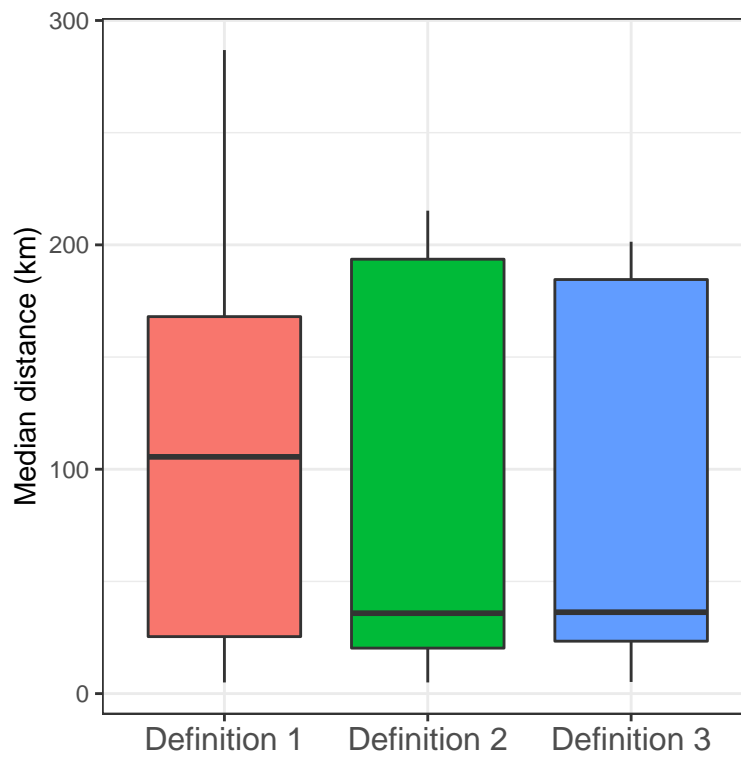


Figure 13: Boxplot showing the median distance between holdings over all pyramids with at least 3 farms and over the different considered definitions of pyramid.

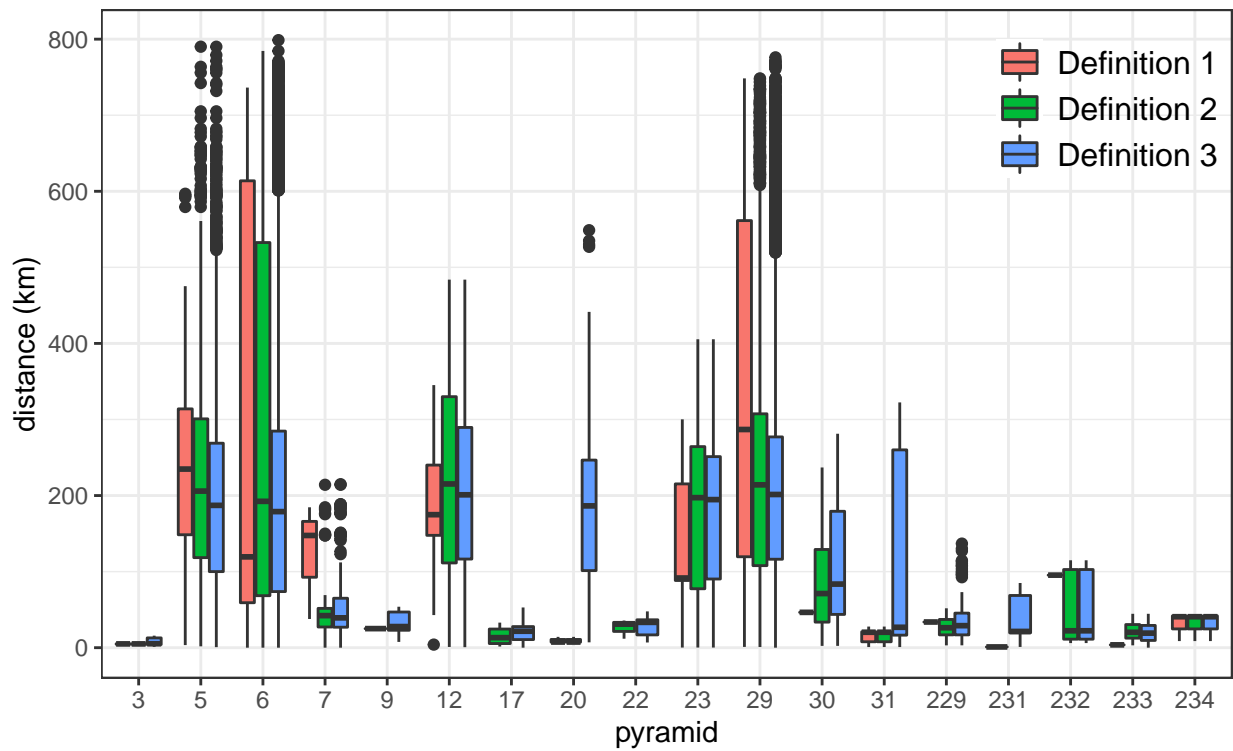


Figure 14: Boxplot showing the distances between farms in registered pig pyramids, for all pyramids with at least two farms. Colours indicate distances computed over the different considered definitions of pyramid.

3.3.2 Movement patterns

Altogether, registered pyramids involved 527 holdings, with 109 T1/T2 holdings, 183 T3 holdings and 235 T4 holdings. However, several T3 and T4 holdings were recorded involved with several registered pyramids. In total, 43 T3 holdings received pigs from >1 registered pyramid, with 26, 11 and 6 T3 holdings receiving pigs from 2, 3 and 4 registered pyramids, respectively. Similarly, 42 T4 holdings received pigs from >1 registered pyramid, with 34 and 7 T4 holdings receiving pigs from 2 and 3 different pyramids, respectively.

When considering all movements occurring during the study period that involved at least one of the 527 holdings involved in the registered pyramids, 2111 unique holdings were selected (or 6.7% of all pig holdings in GB), among which 520 were either PRIMO-approved or T4 holdings. Spatial locations of holdings that received pigs from or sent pigs to one of the holdings involved in the registered pyramids is shown in Figure 15A, whereas the network formed through the movements of pigs between these holdings is shown in Figure 15B. Clearly, pyramids are not isolated from the rest of the industry with 23,972 movements from a pyramid to an holding outside pyramids, organised around 4853 connections, and 2340 movements from an holding outside pyramids to a pyramid organised around 181 connections. In total, 6046 connections were recorded in the network, with 5034 (83%) carried out with a holding outside a pyramid. Although movements events only occurred once for nearly half of these connections (44%) during the study period, 113 connections (2%) showed movement events at least once per month throughout the study period. These includes 66 holdings that are neither involved in registered pyramids nor PRIMO-approved by APHA, among which 52 declared moving pigs under PRIMO in eAML2. Note that none (0) of these holdings were considered as candidates for T4 holdings as they either sent pigs to another holdings or received pigs from non-approved holdings.

We further checked how movements between holdings that are involved in registered pyramids are structured (Figure 16). Overall, 516 holdings were moving pigs within and between registered pyramids, among which only 98 were T1/T2 holdings (i.e. about 90% of the total number of T1/T2 holdings registered by APHA). In contrast, 183 were T3 holdings and 235 were T4 holdings.

The network formed through the movements of pigs between holdings involved in registered pyramids is structured around a large component (that is a unique cluster of holdings that are connected to each other but isolated from the rest of the network, Figure 16A) and 4 smaller components (Figures 16B-16E). While the 4 smaller components involved between 4 and 25 holdings, the largest component involved 469 holdings, which represent 91% of the 516 holdings involved in the network, and 13 of the 19 registered pyramids. By differentiating holdings as a function of their tier, we can clearly see that the movement patterns in the smaller components behave similarly to expected from vertically integrated pyramids, with pigs strictly moving from Tier 1 to Tier 4. In contrast, the largest component is more complex with no clear pattern and a high level of interconnections between holdings. The spatial distribution of holdings involved in each component is shown in Figure 17.

Focusing on the largest component, we looked at how holdings of different pyramids interact with each other.

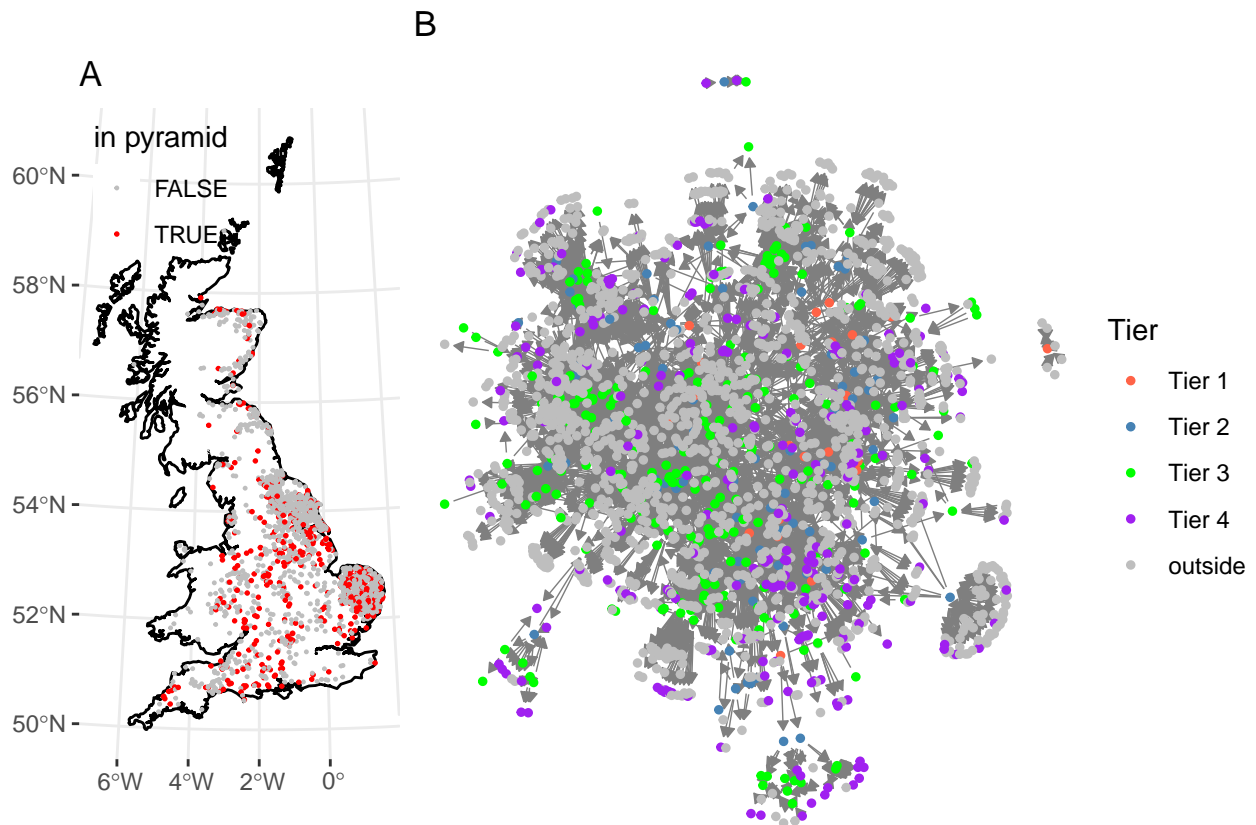
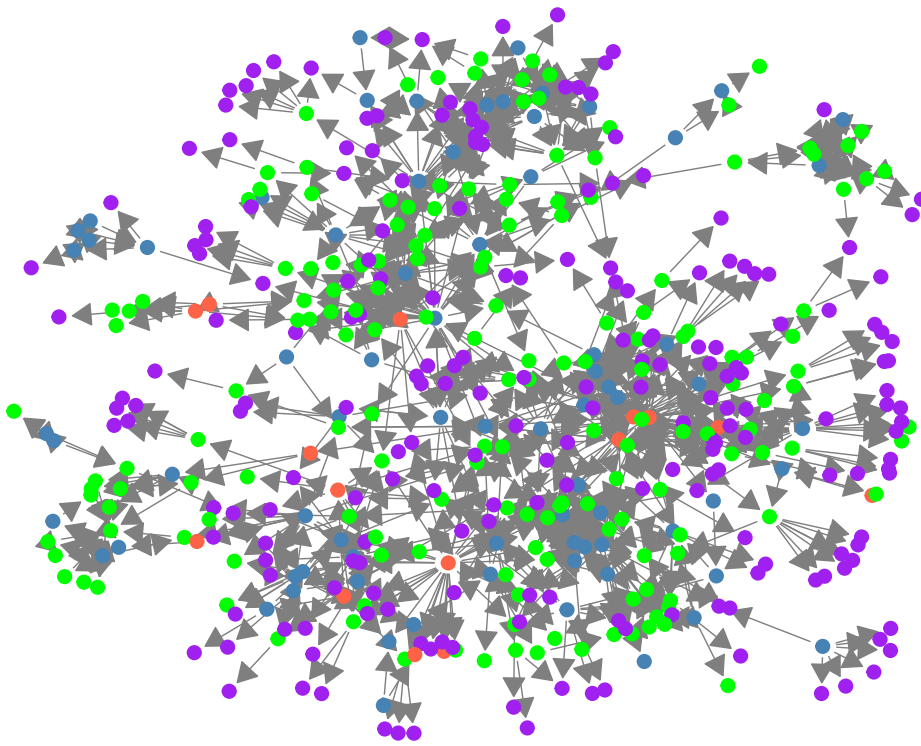


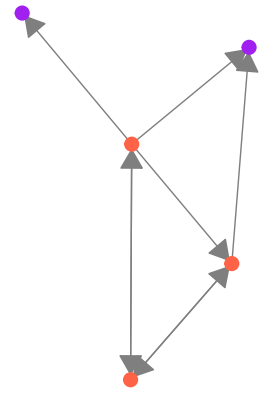
Figure 15: Holdings in contact with pyramids. (A) map and (B) network of all holdings that received or sent pigs to at least one holding involved in pig pyramids. Red and grey dots in (A) indicate holdings that belong to a pyramid and those that do not, respectively. Filled circles in (B) represent pig holdings, whereas arrows represent the movement of at least one pig between two given holdings. Except from outside pyramids, the colour of each circle in (B) represents the tier that holdings belong to.

A

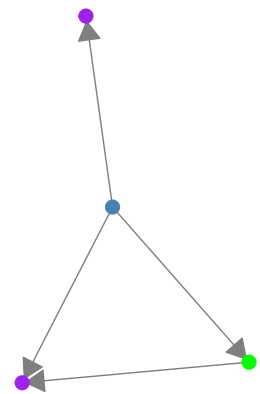
● Tier 1 ● Tier 2 ● Tier 3 ● Tier 4



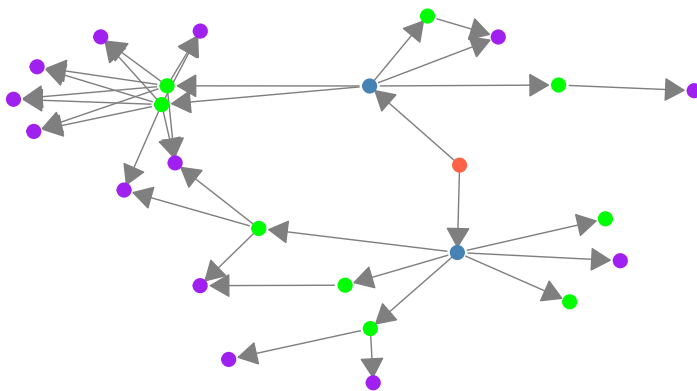
B



E



D



C

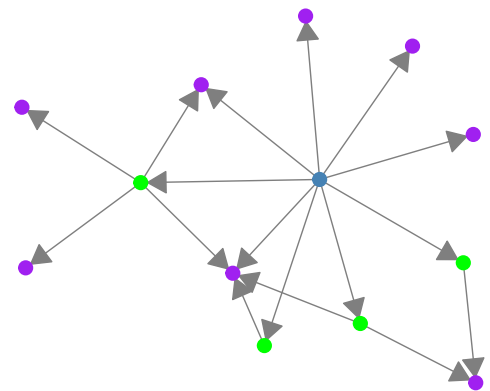


Figure 16: Network of movements between holdings involved in pyramids. Here contact is defined as having at least one movement of pigs between holdings. Filled circles represent individual holdings and lines represent a movement of at least one pig. The colour of each circle represents the tier that holdings belong to. The network is structured around a large component (A) but also include four smaller components (B-E). A component is defined as a unique cluster of holdings that are connected to each other but isolated from the rest of the network.

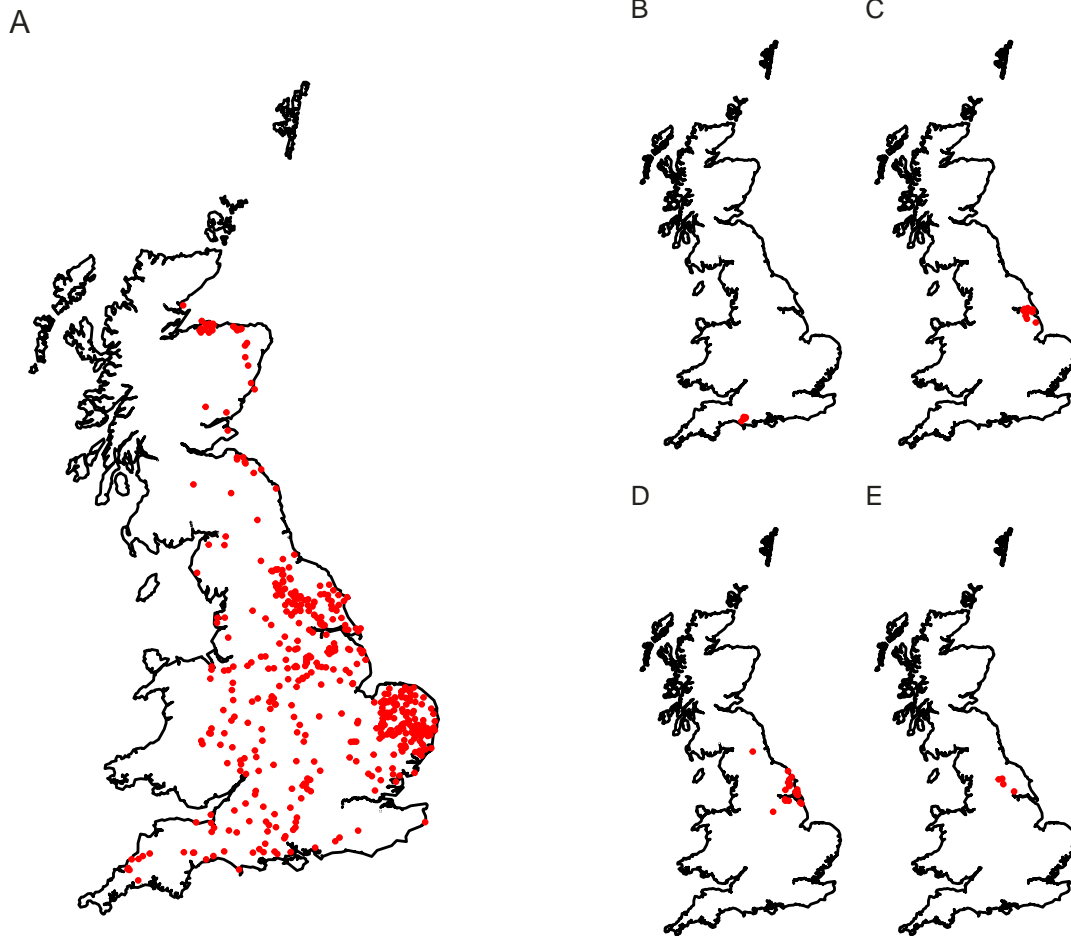
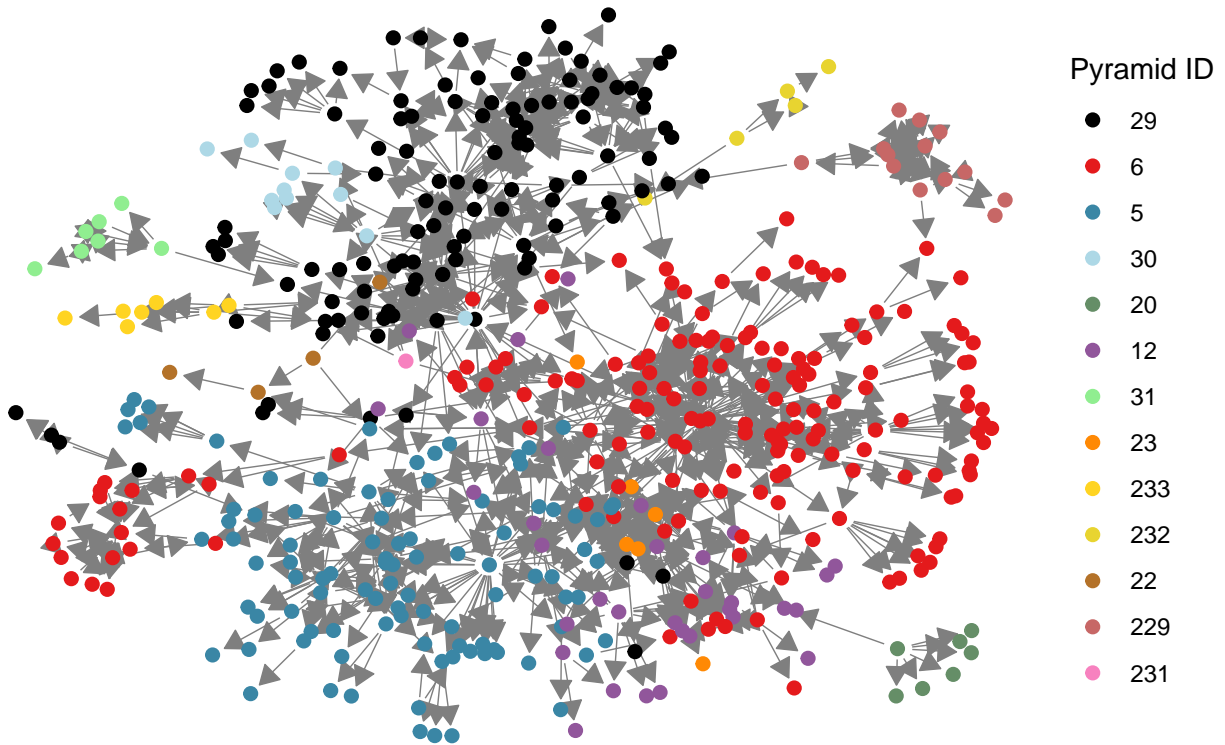
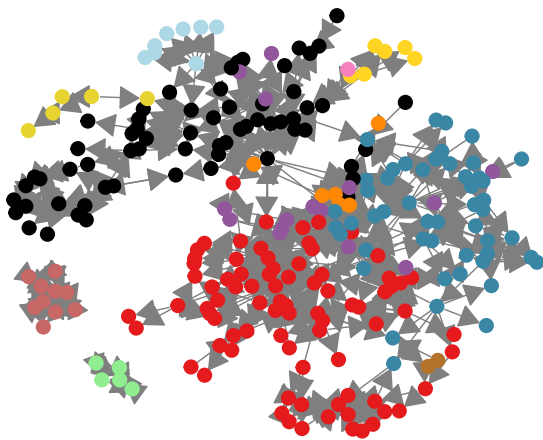


Figure 17: Map showing the location of all holdings involved in the different components of the network of movements between holdings involved in pyramids. Note that all locations were randomly jittered within 10km to ensure confidentiality of farm locations.

A



B



C

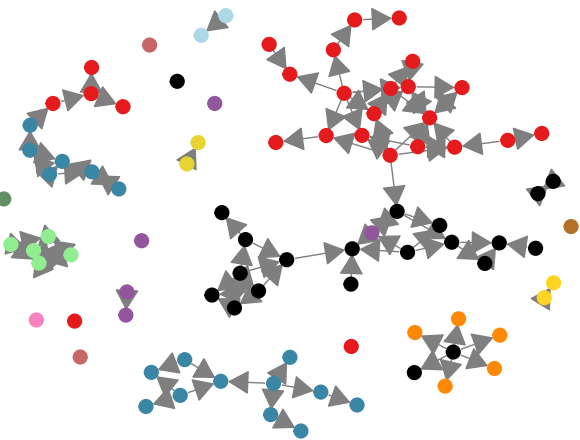


Figure 18: Network of movements between holdings involved in the largest component of holdings involved in registered pyramids. (A) Entire network, involving all holdings from Tier 1 to Tier 4. (B) Similar network, showing only the movement of pigs between holdings of Tier 1 to Tier 3. (C) Similar network, showing only the movement of pigs between holdings of Tier 1 and Tier 2. Here contact is defined as having at least one movement of pigs between holdings. Solid symbols represent individual holdings and lines represent a movement of pigs. The colour of each symbol represents the registered pyramid of which holdings belong to.

During the study period, pyramids were not isolated to each other (Figure 18). However, two patterns of interactions between pyramids can be observed (Figure 18A). On the one hand, holdings belonging to the same pyramid are markedly clustered together and show few connections to the main component (for example, see pyramid #20 or pyramid #31). On the other hand, pyramids can be completely interdependent on each other (see pyramid #23 with #29 or pyramid #5 with #6).

To check how each tier impacts on the structure of the network, individual pig holdings were progressively removed in order of their tier. Figure 18B shows the network when all T4 holdings were discarded and Figure 18C shows when only holdings in the top tiers are considered. It is clear that cross pyramid movements occur at all levels, allowing pyramids to remain connected with each other. Pigs were moving between pyramids through 124 holdings (none outside the largest component of the network) and included 34 holdings from the two top tiers, 63 T3 holdings and 27 T4 holdings. We then tested for the cohesion of this component by progressively removing these 124 holdings involved in cross-pyramid movements (Figure 19). The order at which these holdings were removed was chosen either randomly or through a 'greedy' algorithm which optimises the impact of each removal. For comparison, all holdings involved in the network were also progressively removed in decreasing order of 'in-degree' (i.e. the number of unique holdings that sent pigs to a given holding), 'out-degree' (i.e. the number of unique holdings that received pigs from a given holding) and 'betweenness' (i.e. the frequency a given holding is used to move pigs from an holding to another). Figure 19 indicates that removing only 35 specific holdings from the 124 holdings involved in cross-pyramid movements would be the most efficient strategy to reduce the largest component to a quarter of its current size. These 35 holdings include not only (and unsurprisingly) 22 T1/T2 holdings but also 7 T3 holdings and 6 T4 holdings. The insert in Figure 19 shows the map of these 35 holdings. Note that two (2) were located in Scotland.

Figure 20 shows the network formed by all movements between tiers of individual pyramids recorded during the study period. Most individual cross-pyramid links were down the production chain, with 106 and 27 links from top tiers to T3 and T4, respectively, and 17 links from T3 to T4. While pigs can move across pyramids through 21 links between same tiers (including 10 cross-pyramid links between top tiers), 5 upward links (i.e. moving up the production chain) were also recorded.

To test how resilient the structure of the large component is over time, we looked how the structure of the large component changes when only movements that occurred in either 2016, 2017 or 2018 are considered. Hence, this analysis assesses the impact of changes in ownership and changes in business relationship between 'breeding companies' (i.e. individual registered breeding pyramids involving T1 and T2 holdings only) and 'producing/finishing companies' (i.e. involving T3 and T4 holdings only) upon contacts between pyramids. First, we only considered the network where all T4 holdings were discarded (as in Figure 18B). This is because T4 holdings may legally receive pigs from different pyramids, whereas T3 holdings are required to source their pigs from a single registered pyramid as part of their approval process. Figure 21 showed that the structure of the network remains stable across years despite the 5.4% reduction in the number of holdings (from 242 in 2016 to 229 in 2018) and the 9.1% reduction in the number of connections between holdings (from 508 in 2016 to 462 in 2018).

Looking at the network formed by movements between tiers of individual pyramids occurring in either 2016, 2017 or 2018 (Figure 22), the density of the network (that is the ratio of the number of connections between tiers to the number of possible connections) is relatively stable, with a density of 0.073 in 2016, 0.071 in 2017, to 0.07 in 2018. Although changes in the structure of some pyramids occurred (e.g. with tiers changing source of pigs) and of the network itself (with some pyramids breaking away from the main component), pyramids still remained highly connected. In fact, the observed network densities represented 3.38, 3.19 and 3.15 times more connections than what would be expected from a theorised flow of pigs within a vertically integrated pig sector where all pyramids are isolated from one another.

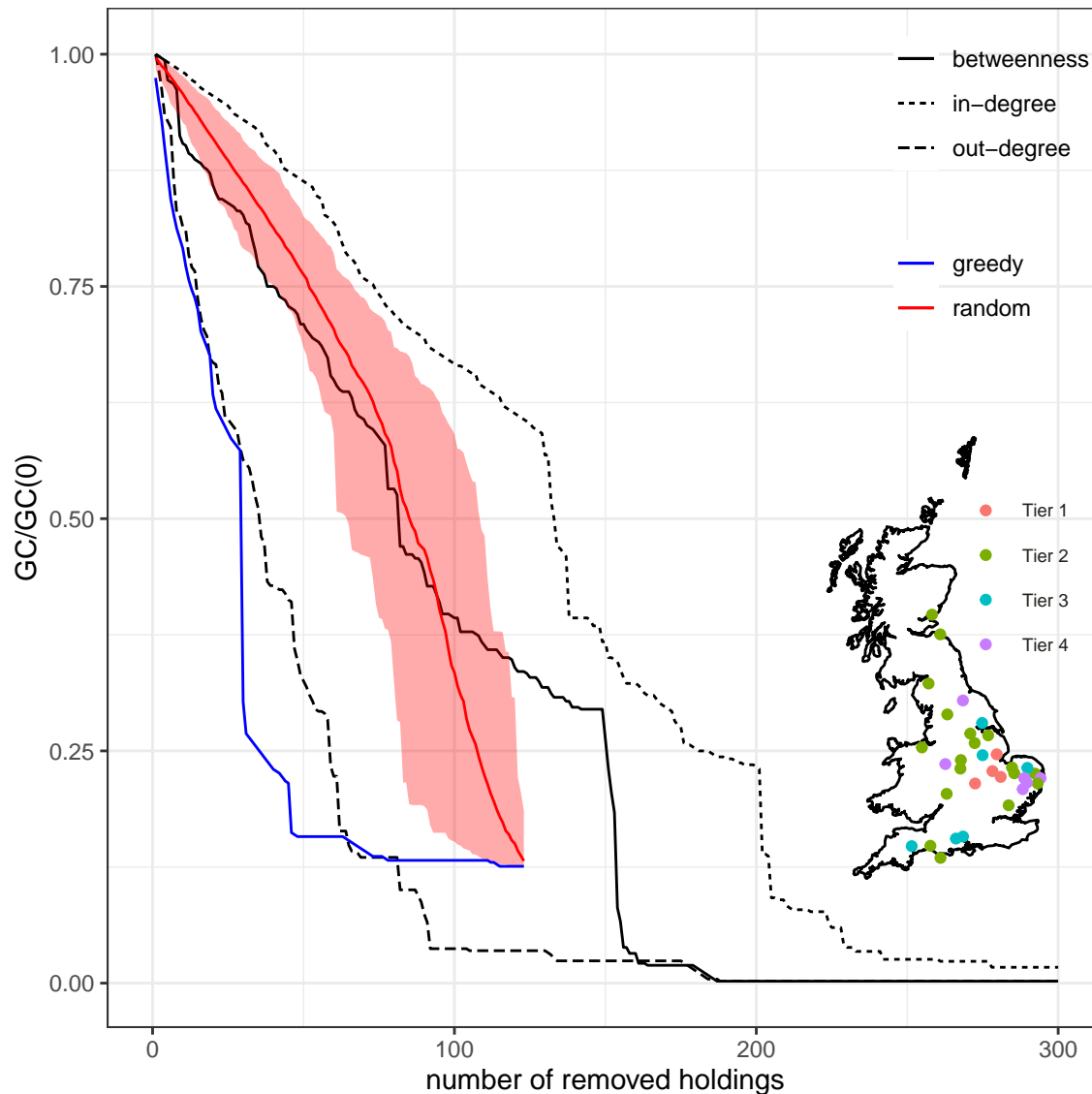


Figure 19: Percolation analysis. Changes to the relative size of the largest component (GC) formed by movements between holdings belonging to a pyramid with progressive targeted removal of holdings. Here, holdings involved in cross pyramid movements were progressively removed, one by one, from the network. The order at which these holdings were removed was chosen either randomly or through a greedy algorithm, optimising the impact of each removal. For comparison, all holdings involved in the network were progressively removed in decreasing order of in-degree, out-degree and betweenness. 'In-degree' is the number of unique holdings that sent pigs to a given holding, 'out-degree' is the number of unique holdings that received pigs from a given holding, and 'betweenness' is the frequency a given holding is used to move pigs from an holding to another. Insert shows the location of the most influencing holdings involved in cross-pyramid movements as identified by the greedy algorithm. Note that all locations were randomly jittered within 10km to ensure confidentiality of farm locations.

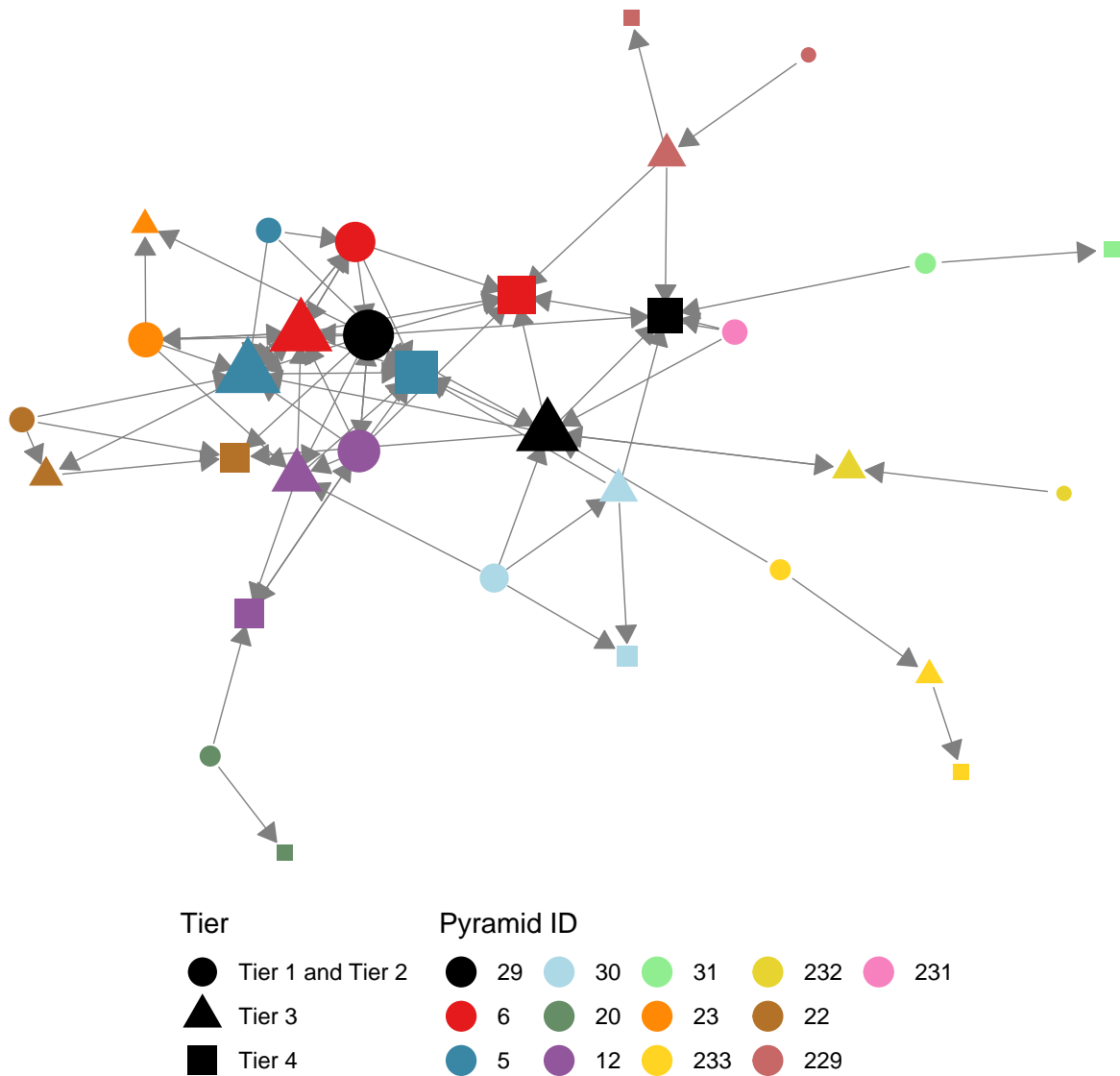


Figure 20: Network of connections between tiers of each pyramid involved in the giant component. Here contact is defined as moving at least one pig between holdings of given tier and pyramid. The shape and colour of the filled symbols indicate the tier and pyramid moving pigs, respectively. The size of each symbol varies as a function of the number of individual tiers-pyramid that are in contact ('degree').

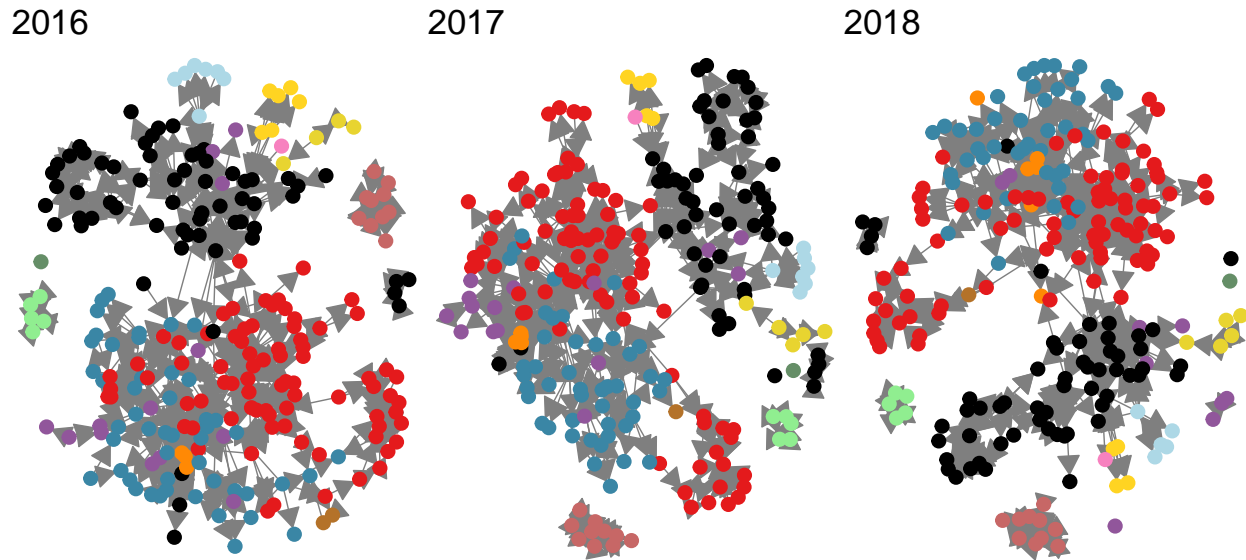


Figure 21: Network of movements between holdings involved in the largest component of holdings involved in registered pyramids. Here is shown only the movement of pigs between holdings of Tier 1 to Tier 3 that occurred in (A) 2016, (B) 2017 and (C) 2018. Here contact is defined as moving at least one pig between holdings of given tier and pyramid. The shape and colour of the filled symbols indicate the tier and pyramid moving pigs, respectively. The size of each symbol varies as a function of the number individual tiers-pyramid that are in contact ('degree').

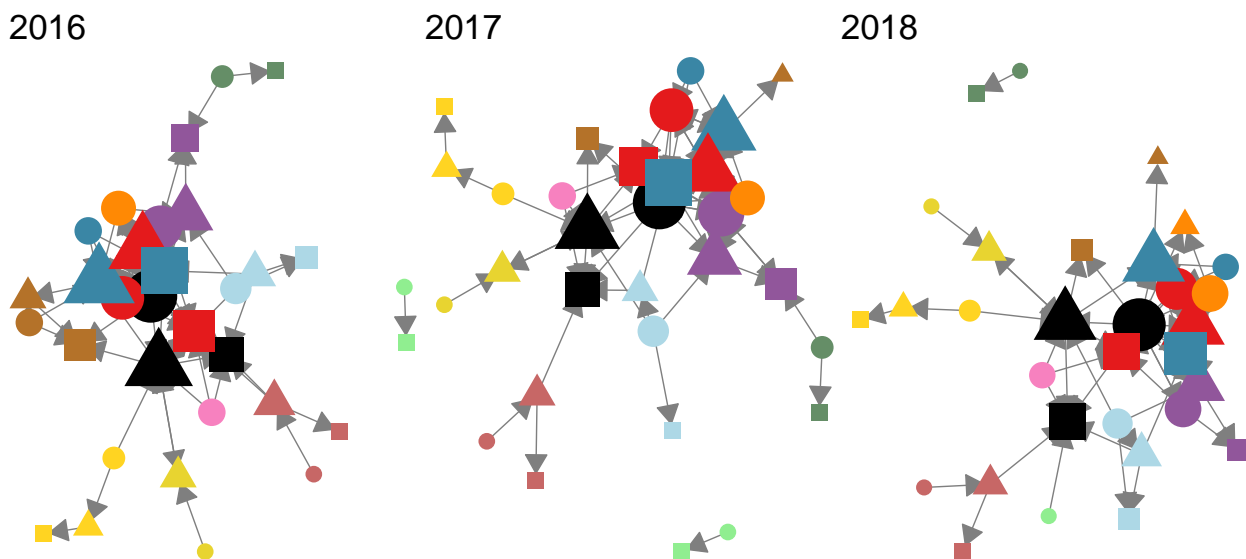


Figure 22: Network of connections between tiers of each pyramid involved in the giant component and moved pigs in (A) 2016, (B) 2017 and (C) 2018.

Table 4: Descriptive statistics of all production pyramids registered in Great Britain during the study period and their movements. Descriptive statistics represent measure per pyramid.

Variable	Total	Mean	Median	Range
Definition 1				
Number of holdings *	109	5.7	3	1 - 27
Total number of batches moving from/to pyramid	26,951	1,418.5	373	50 - 9,258
Number of batches moving within pyramids	3,196	168.2	3	0 - 1,130
Number of batches sent to slaughter	7,336	386.1	79	0 - 2,087
Number of batches sent to market	991	52.2	11	0 - 271
Number of imported batches	25	1.3	0	0 - 10
Number of exported batches	97	5.1	0	0 - 52
Total number of pigs moving from/to pyramid	3,066,446	161,391.9	53,538	4,715 - 726,590
Number of pigs moving within pyramids	646,868	34,045.7	1,140	0 - 171,863
Number of pigs sent to slaughter	660,333	34,754.4	6,999	0 - 178,253
Number of pigs sent to market	28,098	1,478.8	802	0 - 7,331
Number of imported pigs	2,628	138.3	0	0 - 1,236
Number of exported pigs	6,742	354.8	0	0 - 4,318
Definition 2				
Number of holdings *	358	18.8	5	1 - 96
Total number of batches moving from/to pyramid	80,554	4,239.7	1,409	110 - 25,975
Number of batches moving within pyramids	10,499	552.6	136	0 - 5,410
Number of batches sent to slaughter	24,908	1,310.9	476	0 - 7,698
Number of batches sent to market	5,932	312.2	16	0 - 1,604
Number of imported batches	25	1.3	0	0 - 10
Number of exported batches	97	5.1	0	0 - 52
Total number of pigs moving from/to pyramid	18,496,276	973,488.2	344,459	9,501 - 5,041,107
Number of pigs moving within pyramids	1,100,904	57,942.3	13,680	0 - 282,659
Number of pigs sent to slaughter	1,866,848	98,255.2	43,235	0 - 524,867
Number of pigs sent to market	150,020	7,895.8	1,103	0 - 53,653
Number of imported pigs	2,628	138.3	0	0 - 1,236
Number of exported pigs	6,742	354.8	0	0 - 4,318
Definition 3				
Number of holdings *	646	34.0	10	1 - 183
Total number of batches moving from/to pyramid	113,210	5,958.4	1,802	110 - 35,939
Number of batches moving within pyramids	15,774	830.2	221	0 - 6,575
Number of batches sent to slaughter	53,962	2,840.1	718	0 - 16,392
Number of batches sent to market	8,360	440.0	66	1 - 2,335
Number of imported batches	25	1.3	0	0 - 10
Number of exported batches	99	5.2	0	0 - 52
Total number of pigs moving from/to pyramid	21,514,747	1,132,355.1	489,816	19,943 - 5,648,228
Number of pigs moving within pyramids	2,456,311	129,279.5	44,027	0 - 507,560
Number of pigs sent to slaughter	4,532,049	238,528.9	58,942	0 - 1,229,685
Number of pigs sent to market	186,160	9,797.9	1,433	114 - 59,284
Number of imported pigs	2,628	138.3	0	0 - 1,236
Number of exported pigs	6,810	358.4	0	0 - 4,318

Note:

* Some holdings may be present in more than one pyramids.

3.4 Description of non-registered pyramids

Among the 291 WR and WB holdings registered to APHA under PRIMO (i.e. T3 holdings) and 269 T4 holdings previously identified, 108 and 34 respectively were not involved in any of the registered pyramids.

Figure 23 shows the network of movements between T3 and T4 holdings that were not directly trading pigs with registered pyramids. In total, 33 of these T3 holdings (30.6%) and 34 of these T4 holdings (100%) showed movements with each other, forming 18 individual components (Figure 23). These latter will be considered as NR pyramids for the remaining of this work.

These 18 NR pyramids included between 2 and 8 holdings, with half involving 2.5 holdings or less. While most of these NR pyramids ($n = 12$) involve one T3 holding sending pigs to ≥ 1 T4 holding, 4 include more T3 holdings than T4 holdings. It is also worth noting that none (0) of these NR pyramids were isolated from the rest of the pig industry, with 1, 19 and 13 T3 holdings receiving pigs, sending pigs or both to holdings outside pyramids, respectively (Figure 23). In particular, 2 NR pyramids (pyramids nr2, nr7) received pigs from imports. Finally, T3 holdings of NR pyramids received 95 movements from non-approved holdings and sent 2368 movements to non-approved holdings, among which 58 (61%) and 675 (29%) were reported as made under PRIMO in eAML2, respectively.

Figure 24 shows the spatial location of all holdings involved in each identified NR pyramid. Among all holdings involved in NR pyramids, 4 holdings were in Scotland, 63 were in England, and 0 were in Wales. In total, 3 pyramids were partly located in Scotland (Figure 25).

Figure 26 compares the geographical extent of the NR pyramids identified in GB during the study period. Again, pyramids of more than 3 holdings and with holdings located in both England and Scotland, showed the widest spatial extent, with median distances of 110 km and 187 km. In contrast, pyramids with holdings located in a single country showed a smaller spatial extent, with median distances ranging from 10.8 km to 80.4 km (median = 36.1 km).

3.5 T3 holdings not linked to pyramids

Throughout the study period, 75 T3 holdings, or 25.8% of the total number of WR and WB holdings registered to APHA under PRIMO, were not recorded trading pigs with any other PRIMO-approved or T4 holdings. Overall, 32 of these 75 T3 holdings (42.7%) did not participate in any movements of pigs in GB, whereas 43 (57.3%) received or sent pigs. Figure 27 shows the spatial location of these T3 holdings.

Among the 43 active T3 holdings, 8 sent pigs to slaughter only, 12 sent pigs to another pig holding and 22 sent pigs to both (slaughter and non slaughter destinations). In addition, 25 received pigs from another holding, among which 4 sent pigs exclusively to slaughter, 10 sent pigs exclusively to another holdings, and 10 sent pigs to both. Note, one (1) T3 holding showed a single record of receiving pigs (involving a single batch of 6 pigs) but no records of pigs leaving the property within the study period.

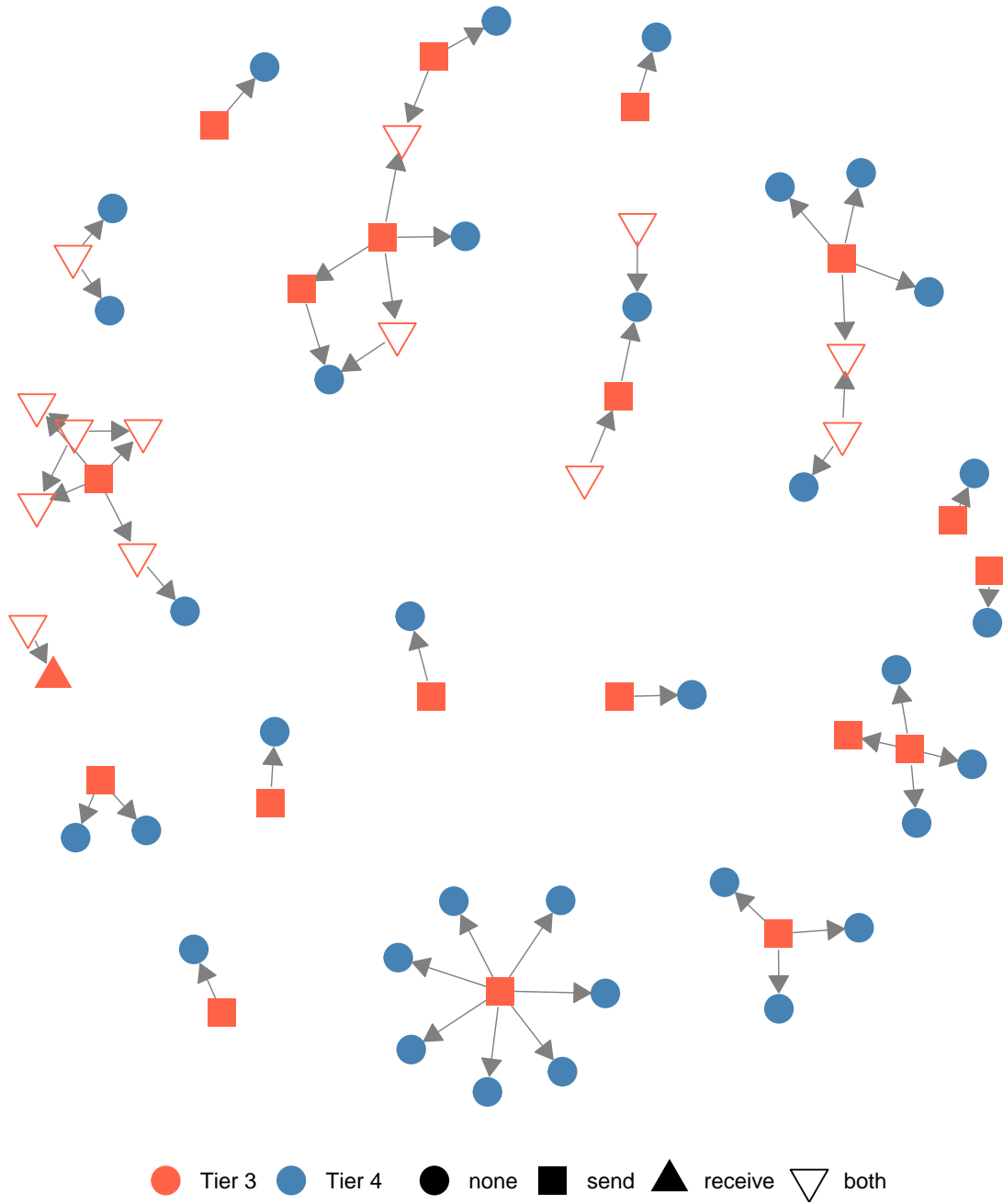


Figure 23: Network of connections between Tier 3 and Tier 4 holdings involved in NR pyramids. Colours inform of tiers, while shape of nodes indicates holdings that sent and/or receive pigs to farms non-considered as part of pyramids

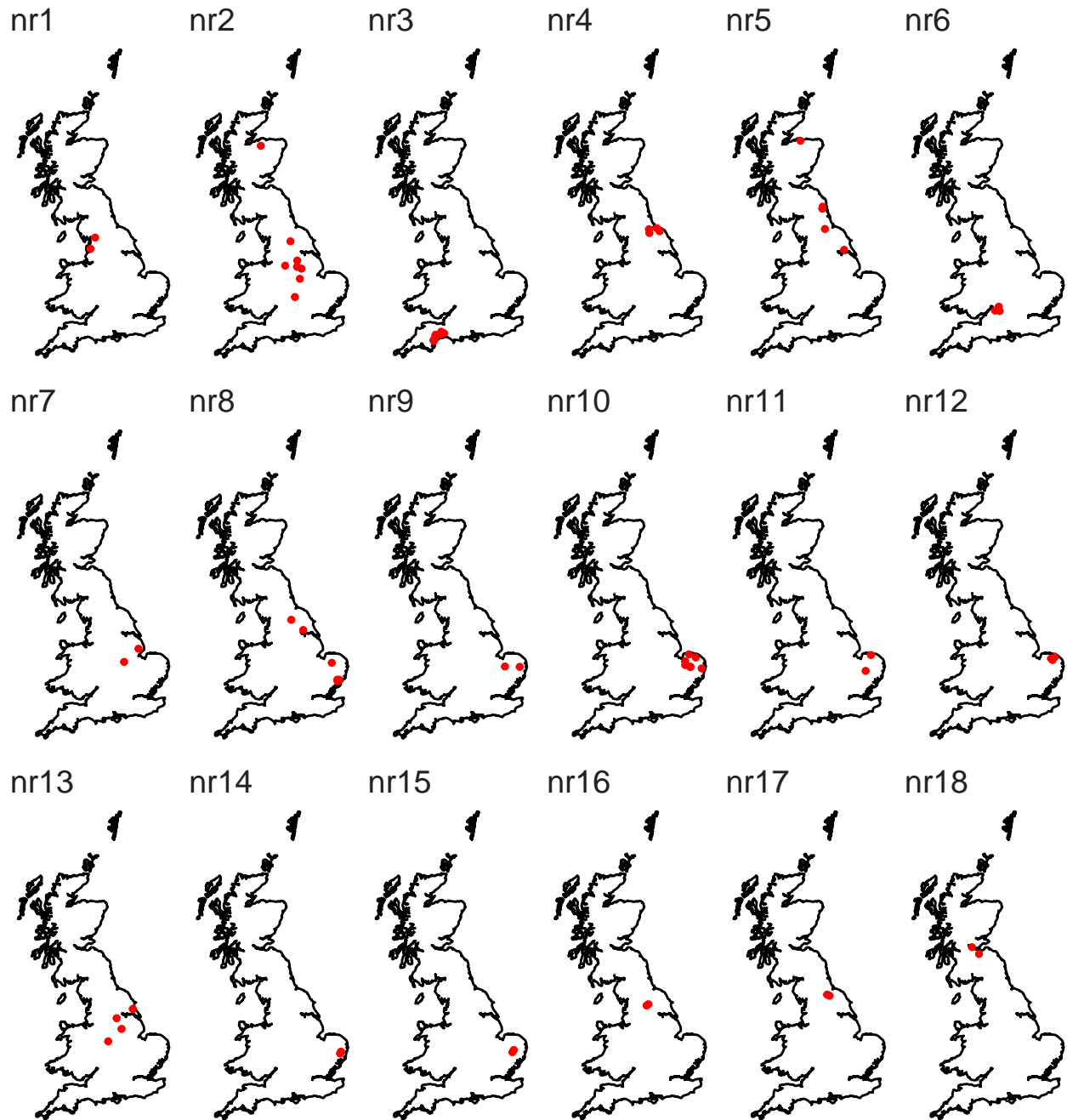


Figure 24: Map showing the location of all holdings involved in NR pyramids in Great Britain. Text at the top of each map indicates the pyramid identifier. Note that all locations were randomly jittered within 10km to ensure confidentiality of farm locations.

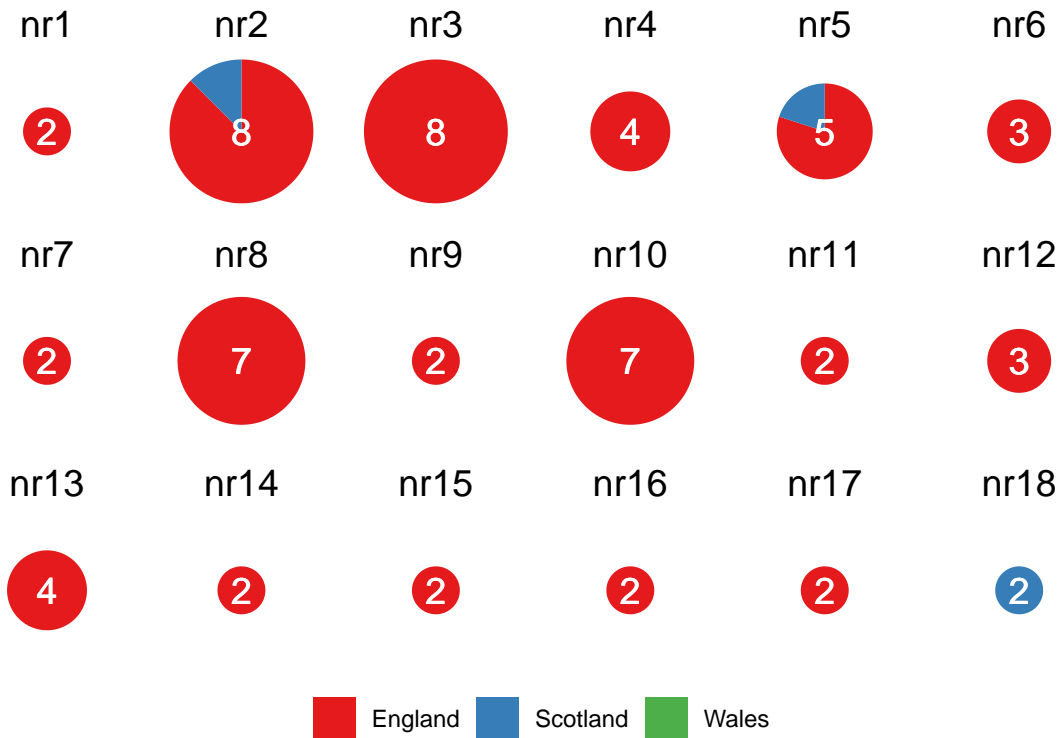


Figure 25: Pie chart showing the proportion of Scottish, Welsh and English holdings in NR pyramids. Number at the top of each pie chart indicates the pyramid identifier, while the size and number at the centre represent the total number of holdings involved in each pyramid.

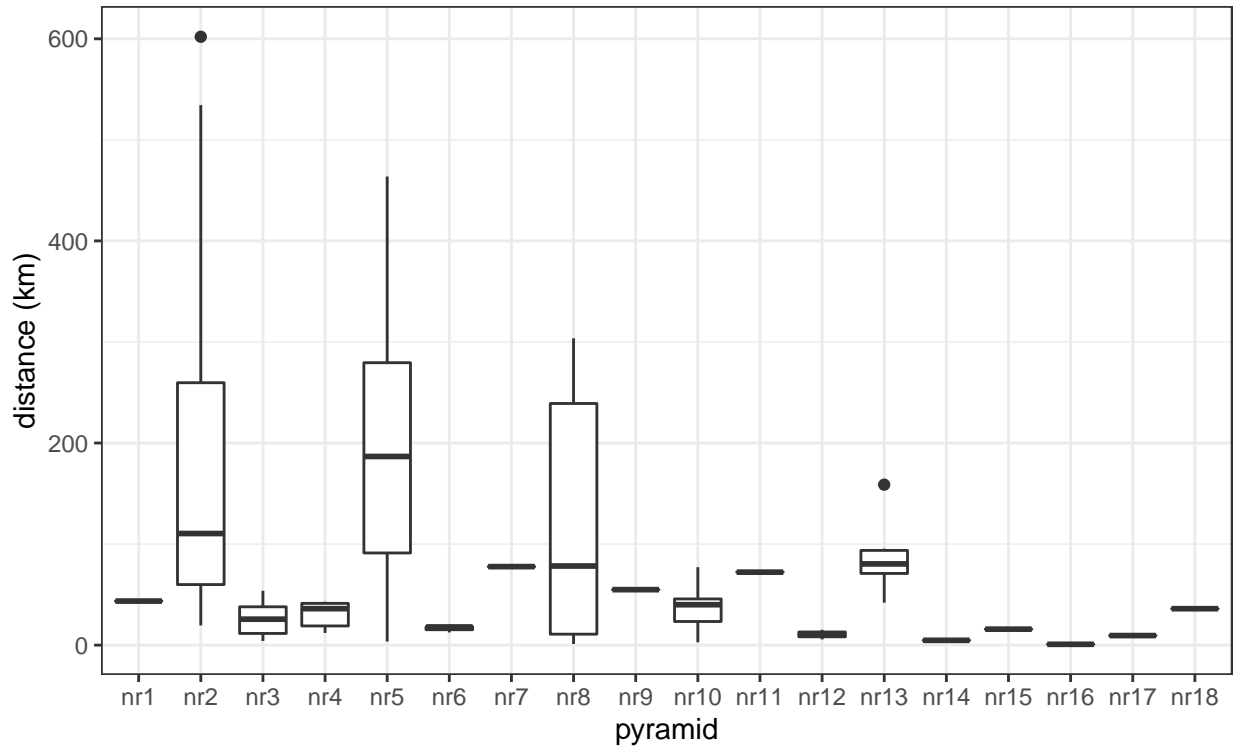


Figure 26: Boxplot showing the distribution of distances between all farms involved in each identified NR pyramid. Here, we computed the euclidean distance (straight line) for all pyramids with at least two farms and was measured in kilometre (km).

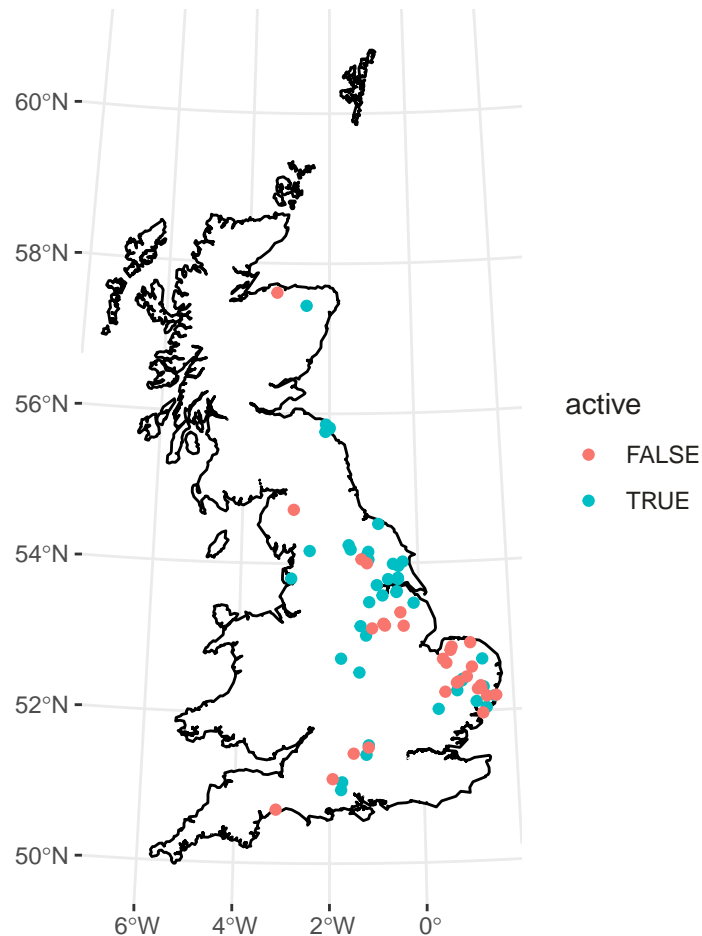


Figure 27: Map showing the location of all PRIMO-approved T3 holdings that were not involved in pig production pyramids during the study period. Colour indicates holdings that were recorded as moving pigs during the study period. Here, we define active holdings as those showing at least one record of pigs moving in or out. Note that all locations were randomly jittered within 10 km to ensure confidentiality of farm locations

Over the three years of the study period, the 34 T3 holdings that sent pigs to other pig holdings carried out a median of 21.5 (min-max: 0.33 – 59) movements per year. In total, these T3 holdings sent a median of 18,922 pigs (min-max: 20 – 88,438) to other pig holdings over the study period. On average, these T3 holdings sent pigs to 4 different holdings (min-max = 1 – 54), none of which were PRIMO-approved or exclusively sending pigs to slaughter. In addition, 20 of these T3 holdings received pigs, sourcing pigs from between 1 and 54 other holdings (median = 1). As a consequence, 34 T3 holdings were involved in the largest component formed by all pig movements outside pyramids (either registered or non-registered). This latter component involved 27,481 premises, including 66 markets and 22 showgrounds, and represents 86.4% of all premises involved in the pig industry during the study period.

3.6 Impact of movement restrictions

3.6.1 Movements between holdings

Between January 2016 and December 2018, 156,645 batches of pigs were moved within GB from one pig holding to another, corresponding to a weekly average of 985 (95% CI 472 – 1207) batches. In total, 28,134,011 pigs moved between holdings, averaging a number of 176,980 (95% CI 134,338 – 205,811) pigs per week. Over the entire study period, 646,868, 1,025,478, 2,201,019 and 2,499,591 pigs moved within pyramids as defined by either Definition 1, 2, 3 and 3NR, respectively. These represent 4.75%, 7.54%, 16.2% and 18.4% of all non-slaughter pigs moving from holdings involved in pyramids (either to holdings involved in other pyramids or to non-approved farms), and 2.3%, 3.64%, 7.82% and 8.88% of all non-slaughter pigs moving in GB.

Figure 28 shows the cumulative number of batches and animals that were moved within pyramids for increasing distances during the study period in GB. Among the 2,499,591 pigs moving within pyramids as defined by Definition 3NR, half the pigs were travelling for 39.8 km or less, with 20.5%, 33.2% and 65.7% of pigs moved within 10km, 20km and 50km, respectively. For comparison, 14.5%, 32.3% and 65.6% of all pigs that moved outside pyramids travelled for less than 10km, 20km and 50km, respectively. It is also worth noting that these figures remain similar across all definitions of pyramid considered in this report (Figure 28).

We further explored how distance-based restrictions may perturb the flow of pigs within pyramids by reconstructing the network formed by movements that would have been granted licence over the entire study period. Here, we assumed that all movements recorded during the study period represent potential trade routes which can be activated by farmers when facing movement restrictions. Figure 29 shows the structure of the network when only movements of less than 10km (Figures 29A), less than 20km (Figures 29B) and less than 50km (Figures 29C) are granted a movement licence under derogation. Networks formed by movements of less than 10km, 20km and 50km involved 4, 2.5 and 1.4 times less holdings than the unrestricted network, respectively. Additionally, they are clearly more fragmented, with 10 to 15 times more components (Table 5). While these components are of small size, with the largest including 6 holdings (for movements of less than 10km) to 20 holdings (for movements of less than 50km), most of the holdings involved in pyramids would still be able to move pigs to other holdings. Table 5 shows the proportion of T1, T2, T3 and T4 holdings of registered and non-registered pyramids moving pigs under different scenarios of distance-based derogations. Under the 50km derogation, 73 (74.5%) T1/T2 holdings and 143 (66.2%) T3 holdings were able to move pigs, whereas only 148 (55%) T4 holdings would be participating in the movement of pigs. Despite this, 65.3% of the trade routes were stopped, representing 40.6% of all batches moved during the study period (Table 5). These restrictions would mostly affect T1/T2 holdings, with only 42.2%, 33.1% and 15.5% of the trade routes allowed to proceed to T1/T2 holdings, T3 holdings and T4 holdings, respectively. For comparison, 61.5% and 66.7% of all trade routes from T3 holdings would be allowed to move (Table 5).

To estimate the benefit of each considered distance-based derogation for the entire British pig industry, we evaluated the average number of pigs that would be allowed to move when facing an outbreak of exotic

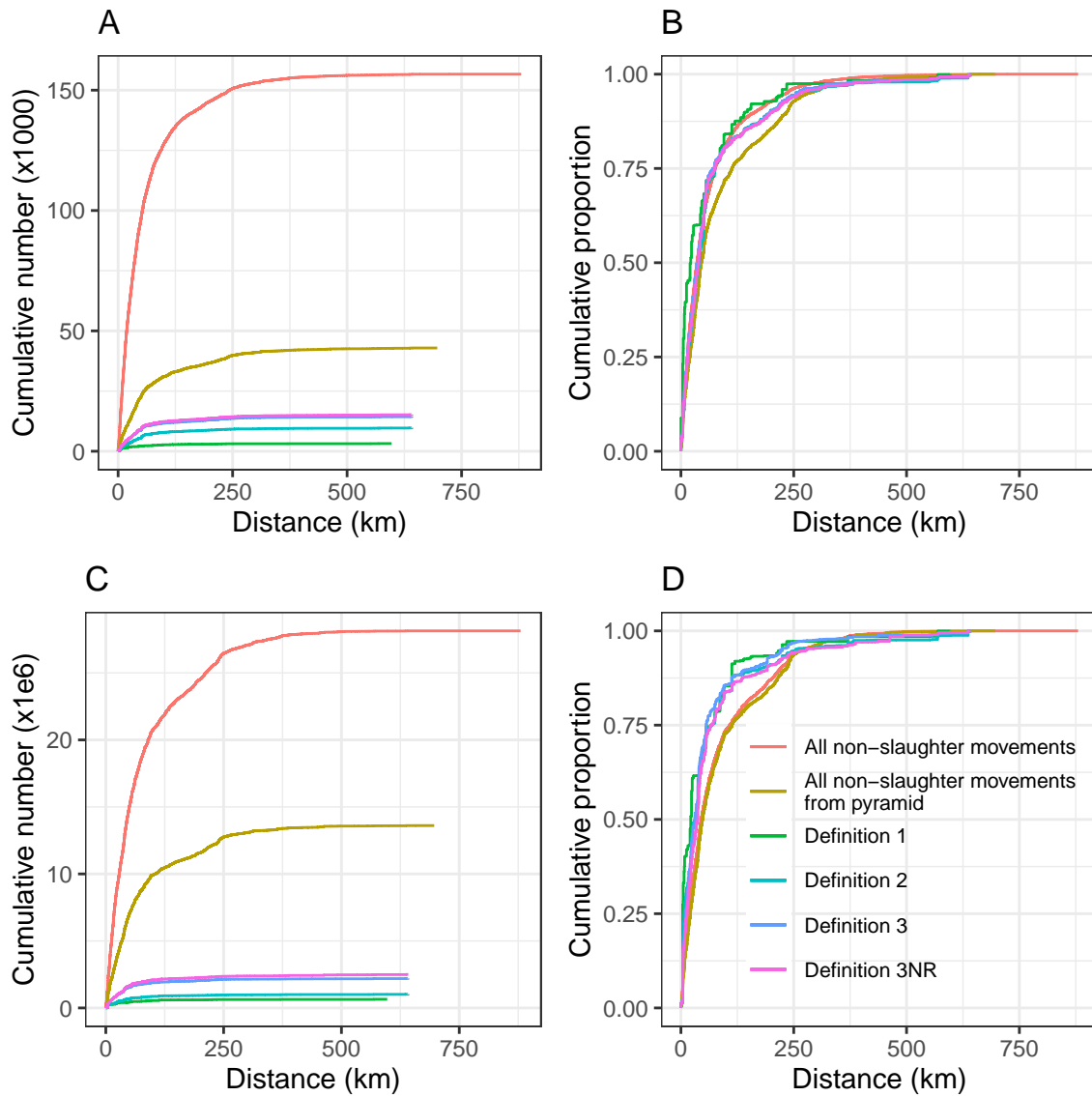


Figure 28: Cumulative number of non-slaughter batches and non-slaughter pigs moved in GB during the study period as a function of distance travelled. Here is shown (A) the cumulative number of non-slaughter batches, (B) the cumulative proportion of non-slaughter batches, (C) the cumulative number of non-slaughter pigs and (D) the cumulative proportion of non-slaughter pigs for each definition of pyramid considered. For comparison, we also show information for all farm-to-farm movements recorded in GB during the study period.

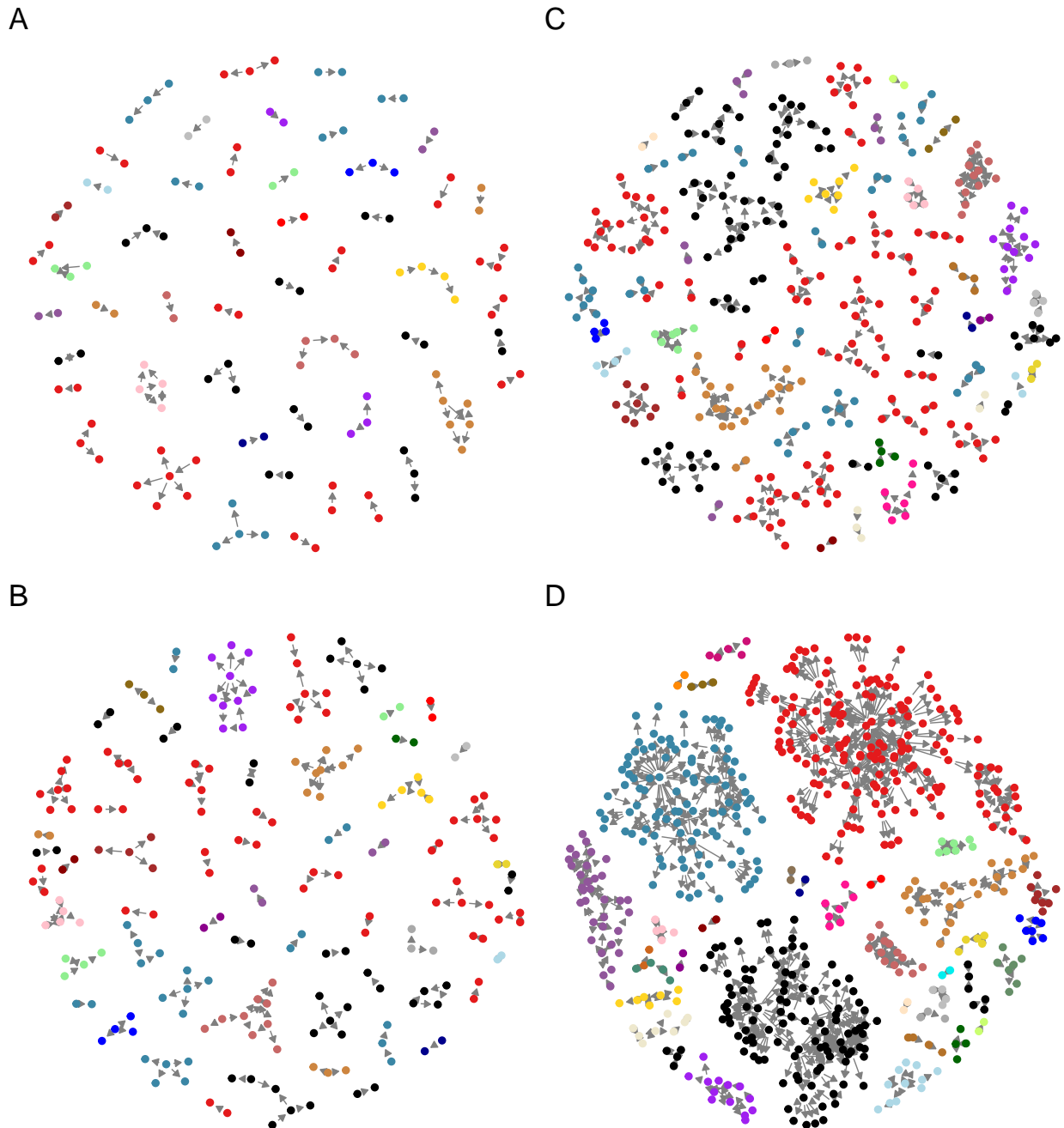


Figure 29: Network formed by holdings involved in registered and non registered pyramids after MRZ is implemented and for various scenarios of distance-based derogations. Here, only movements within pyramids will be allowed to move if travel distance is (A) $< 10\text{ km}$, (B) $< 20\text{ km}$ and (C) $< 50\text{ km}$. (D) Network formed by all movements within pyramids, irrespective of the distance travelled. Here, all cross-pyramid movements were discarded from the analysis. For clarity, nodes were coloured as a function of the pyramid they belong to.

disease. To do so, we first considered that restrictions on movements would be enforced for a given period of time (i.e. the outbreak duration) and evaluated how the number of pigs would vary for incursions occurring on each Monday of the study period. We assumed that for each definition, the restrictions would remain consistent over the duration of the outbreak. Figure 30 shows the proportion of all non-slaughter pigs that would have been allowed to move to another pig holding with increasing periods of restriction (in weeks from 1 to 26) and for the different scenarios of movement restriction (i.e. derogation strategies and pyramid definitions). None of the pyramid definitions considered in this report allowed more than 10% of the pigs in GB to move to another holding over the course of an outbreak, irrespective of the distance considered. In fact, defining pyramids with Definitions 1 (i.e. considering only breeding companies and including only T1 and T2 holdings) would rarely allow more than 2% of the pigs to move over the course of an outbreak, irrespective of the distance considered, whereas the largest proportion of pigs allowed to move was observed when defining pyramids by including all holdings involved in registered and non-registered pyramids (i.e. *Pyramid Definition 3NR*) and when restricting movements with distance greater than 50km only. In this scenario, derogations for movements within pyramids of <50km would only allow 5.95% (95% range 5.56% – 7.05%) of the total number of pigs moved within GB, irrespective of the length of time within which movement restrictions are enforced.

Overall, 200,026 (95% range 182,337 – 223,300), 2,162,828 (95% range 2,032,630 – 2,335,047) and 4,643,616 (95% range 4,418,168 – 5,025,133) pigs moved from any given holdings within a period lasting 1, 12 and 26 weeks, respectively, among which 48.2% (95% range 44.6% – 52.4%), 49.2% (95% range 46.2% – 50.3%), and 49.4% (95% range 46.8% – 50.3%) departed from pyramids as defined by Definition 3NR. Assuming restrictions were in place for 12 weeks and if pyramids were defined as Definitions 3 and 3NR, licences granted for movements of less than 50km within pyramids would have allowed a median of 123,838.5 (95% range 106,074.8 - 131,271.7) and 132,424 (95% range 114,231.6 – 140,473.9) pigs to move, respectively, which only represents 5.52% (5.19% - 6.02%) and 5.92% (5.61% – 6.52%) of all pigs that were to be moved in GB. For comparison, derogations based on Pyramid Definitions 1 and 2 would have allowed a median 34,066.5 (95% range 29,274.12 – 37,458.3) and 54,726 (95% range 45,750.4 – 59,547.88) pigs to move, respectively; these represent only 1.55% (1.43% – 1.72%) and 2.49% (2.22% – 2.73%) of all pigs that were to be moved in GB.

Nevertheless, when considering derogations upon movements occurring within pyramids only, less than half of the pigs will be able to move to another holding if restrictions for movements of more than 20km are enforced. In contrast, allowing movements between holdings of <50km within the same pyramid would enable more than 65% of the pigs to move, irrespective of the pyramid definition considered (Figure 31). In particular, allowing movements of <50km between holdings belonging to the same pyramid as defined by *Pyramid Definition 3NR* would allow 65.5% (95% range 61.5% – 69.8%) of the pigs moving within pyramids to move.

Table 5: Movement pattern of holdings involved in registered and non-registered pyramids after MRZ is implemented and for various scenarios of distance-based derogations.

variable	Distance-based movement derogations		
	<10km	<20km	<50km
Number of holdings moving pigs	130 (25.2%)	207 (40.1%)	364 (70.5%)
Number of trade routes	86 (8.5%)	165 (16.3%)	352 (34.7%)
Number of batches allowed to move	2855 (18.5%)	4558 (29.5%)	9172 (59.4%)
Number of components	52	63	77
Size of the largest component	6	10	20
Number of holdings moving pigs per tier			
T1 and T2 holdings	38 (38.8%)	45 (45.9%)	73 (74.5%)
T3 holdings	48 (22.2%)	75 (34.7%)	143 (66.2%)
T4 holdings	44 (16.4%)	87 (32.3%)	148 (55%)
Number of trade routes per tier			
From T1/T2 to T1/T2 holdings	19 (18.6%)	22 (21.6%)	43 (42.2%)
From T1/T2 to T3 holdings	14 (4.7%)	31 (10.4%)	99 (33.1%)
From T1/T2 to T4 holdings	11 (5%)	19 (8.7%)	34 (15.5%)
From T3 to T3 holdings	5 (9.6%)	12 (23.1%)	32 (61.5%)
From T3 to T4 holdings	37 (17.1%)	81 (37.5%)	144 (66.7%)

3.6.2 Movements to slaughter

During the study period, 374,562 batches of pigs moved directly to slaughter in GB, involving a total of 25,834,734 animals. Among these, only 2 batches, involving 6 pigs, did not have proper spatial location of their departures. In total, 374,560 batches had informed location for both departure and destination, representing a total of 25,834,728 animals. These correspond to an average of 2356 (95% CI 1004, 2783) batches and 162,483 (95% CI 98,546, 182,291) pigs per week. Note here that, no movement to slaughter via a market was considered in the analysis, assuming that if MRZ is implemented, those movements would not be allowed to proceed.

Over the 25,834,728 pigs sent to slaughter during the study period, 660,333, 1,640,110, 3,828,153 and 4,286,066 pigs were moved directly to slaughter from a pig holdings belonging to a pyramid as defined by either Definition 1, 2, 3 and 3NR, respectively. These represent 15.4%, 38.3%, 89.3% and 100% of all slaughter pigs moving from a holding involved in a pyramid, and 2.56%, 6.35%, 14.8% and 16.6% of all pigs sent to slaughter in GB. In contrast, 26,106,022 pigs were moved within GB from an agricultural holding to a gathering place (i.e. either a collection centre, show, market, ferry or slaughterhouse), including 4,453,828 pigs (17.1%) directly moving from a pyramid as defined by Definition 3NR (i.e. the most inclusive definition of pyramid) to a gathering place.

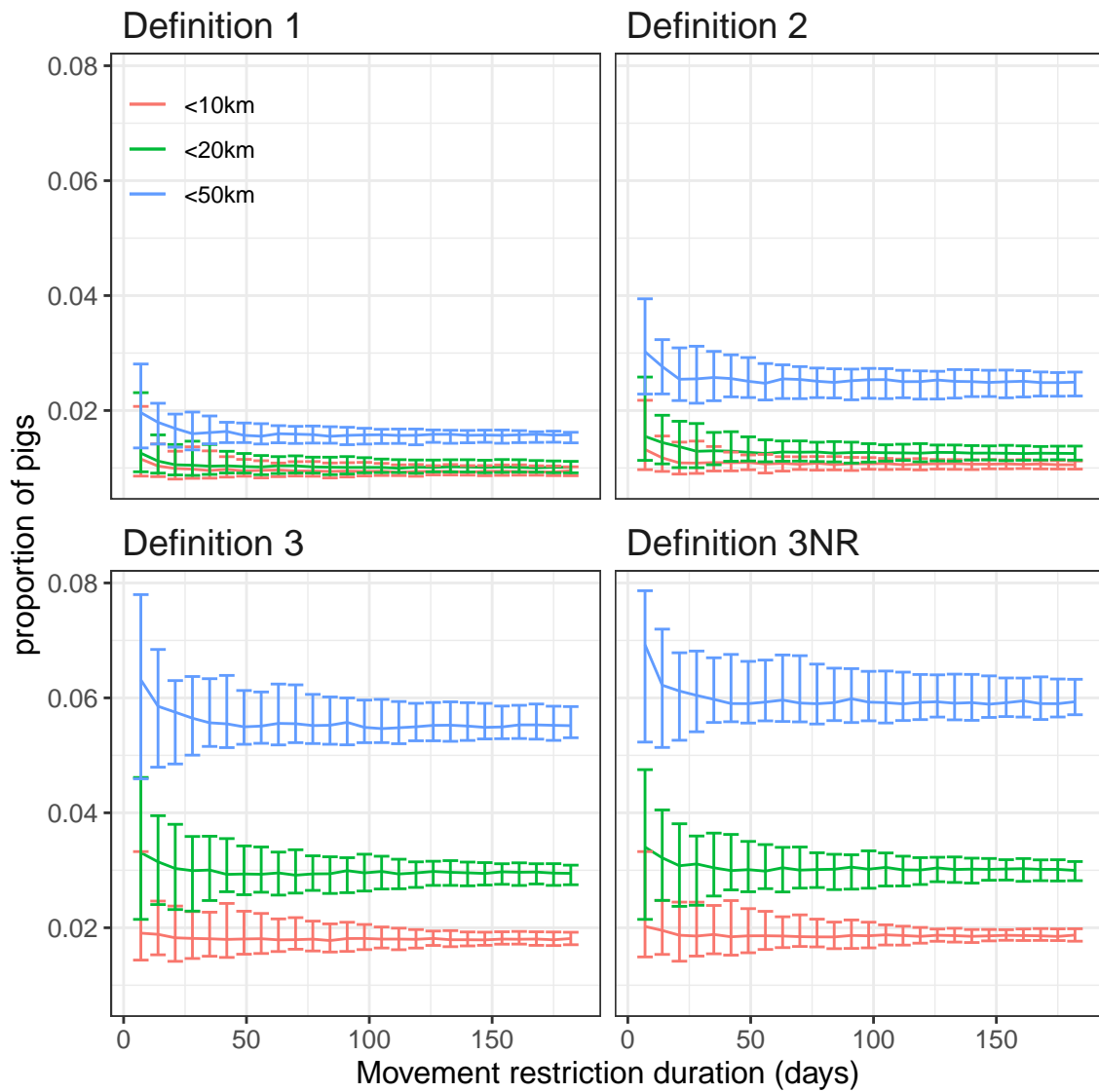


Figure 30: Proportion of the total number of pigs that were allowed to move in GB as a function of increasing periods under movement restrictions. The period of movement restrictions was assumed to range from 1 to 26 weeks. Solid line and error bars represent the median and 95% range of the proportion of the total number of pigs that were allowed to move when different scenario of movement derogations are introduced within pyramids and for different definitions of pyramid.

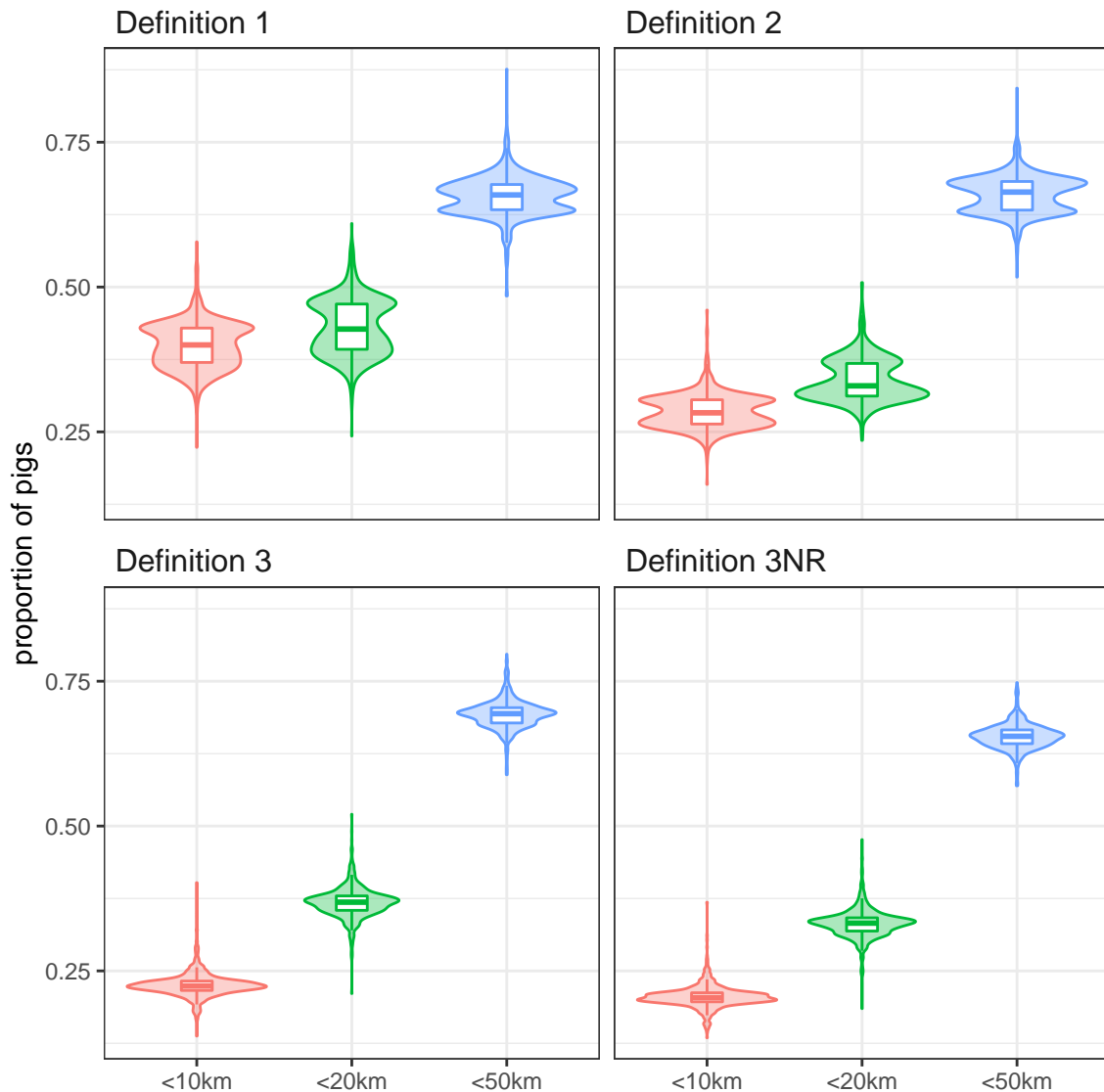


Figure 31: Proportion of the total number pigs that were allowed to move within pyramids for different derogation strategies. Boxplots inside violin distribution provide information of the median and 75% range of the proportion of the total number of pigs that were allowed to move when different scenario of movement derogations are introduced within pyramids and for different definition of pyramid, irrespective of the period of movement restrictions.

Figure 32 shows the cumulative number of batches and animals that were moved to slaughter in GB from any given holdings involved in a pyramid and for increasing distances during the study period. Among the 4,286,066 pigs moving to slaughter from an holding belonging to a pyramid as defined by Definition 3NR, half were travelling for 59.1 km or less, with 2.55%, 6.56% and 28.1% of slaughter pigs moved within 10km, 20km and 50km, respectively. For comparison, 13.4%, 30.9% and 64.4% of all pigs that moved to slaughter from outside pyramids travelled for less than 10km, 20km and 50km, respectively. It is also worth noting that pigs sent to slaughter from T1/T2 holdings (i.e. *Pyramid Definition 1*) tend to move longer distances than the rest of the pigs from T3 and T4 holdings (Figure 32).

3.7 Standstill analysis

Here, we explore how the time between the date of departure and the dates of all arrivals onto premises may vary between pig holdings within and outside pyramids. In the UK, pig holdings are required to keep pigs on farm for a minimum of 20 days prior to any non-slaughter movements. This standstill is designed to prevent diseases spreading widely in the pig population. Derogations to standstill restrictions exist to enable an easy flow of pigs within vertically integrated pyramids. It is therefore expected that only few (from 14.8% to 10.9%) movements would respect standstill regulations among all batches of pigs moving within pyramids during the study period (Table 6). To contrast this figure with the rest of the pig holdings in GB, we categorised pig holdings into three groups (Figure 3): (i) those that received pigs from pyramids but did not meet the criteria for being included as a T4 holding (*Down*), (ii) those that received pigs from the T3 holdings that were not involved in pyramids (either registered or not) and did not meet the criteria for being included as a T4 holding (*Isolated*), and (iii) all holdings that did not trade pigs with PRIMO-approved holdings (*Others*). Figure 33 shows the cumulative number and cumulative probability of movements as a function of their observed standstill duration for all categories of holdings considered. Overall, 7.9% to 25.3% of the movements from holdings outside pyramids would occur less than 20 days after the arrival of pigs onto premises. In total, these represent 10,346 movements, involving 1233 unique pig holdings (Table 6). Among these 1233 pig holdings, 410 (33.3%) were characterised as small holders from their movement records and 485 (41%) reported movements as made under PRIMO in the eAML2 database.

To check if these 1233 pig holdings regularly sent pigs less than 20 days after the arrival of pigs onto premises, the cumulative distribution of holdings was plotted as a function of the observed proportion of movements with a standstill of less than 20 days (Figure 34). Clearly, this behaviour was common among this population of holdings, with half of the holdings moving pigs less than 20 days after arrivals in more than 36.4% to 100% of the time. The spatial location of all farms showing at least one movement that appear to breach standstill regulations and those where more than half of their movements appear to breach standstill regulations are shown in Figure 35.

4 Discussion

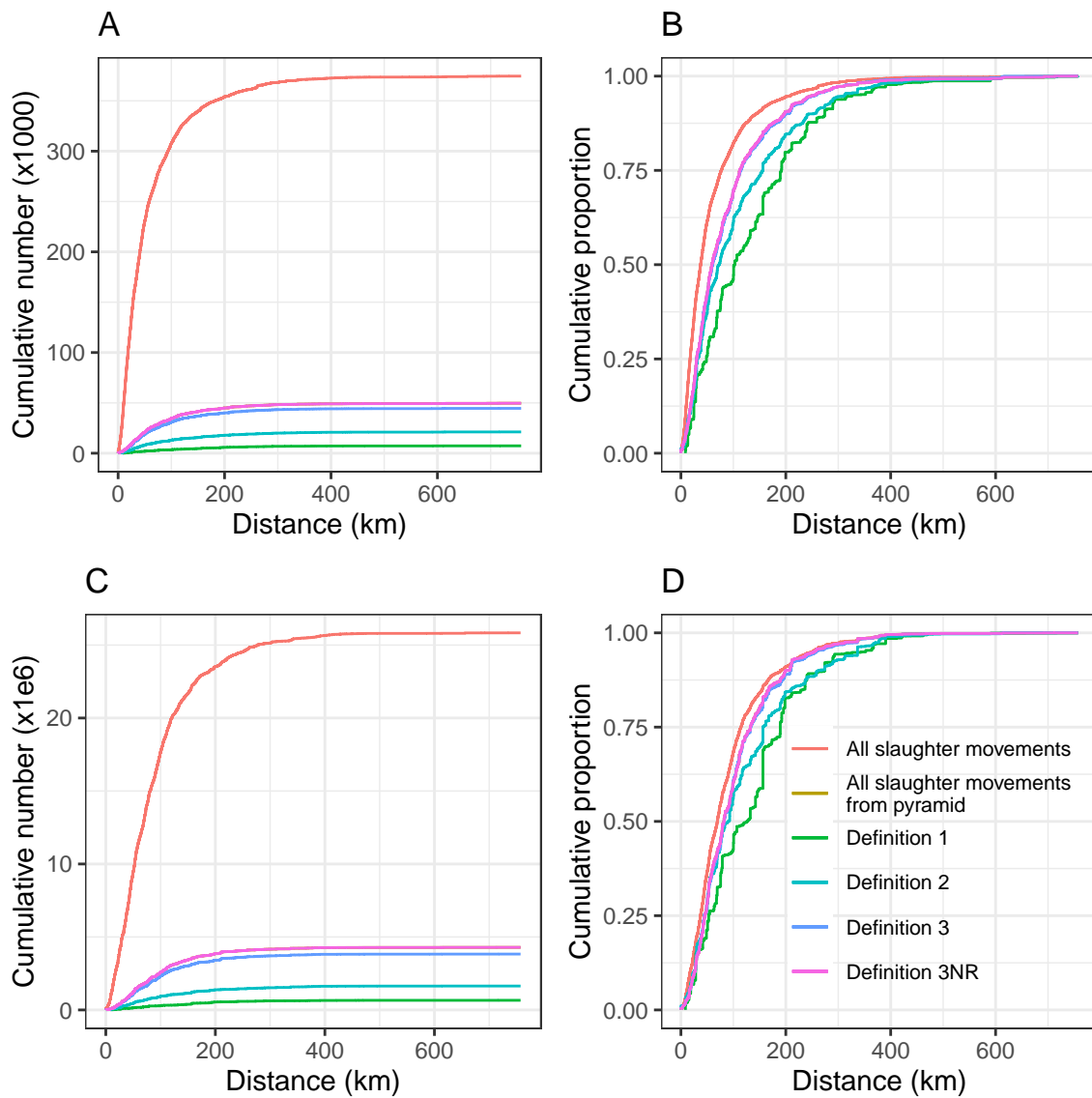


Figure 32: Cumulative number of batches and pigs moved to slaughter in GB during the study period as a function of distance travelled. Here is shown (A) the cumulative number of batches, (B) the cumulative proportion of batches, (C) the cumulative number of pigs and (D) the cumulative proportion of pigs for each definition of pyramid considered. For comparison, we also show information for all farm-to-farm movements recorded in GB during the study period.

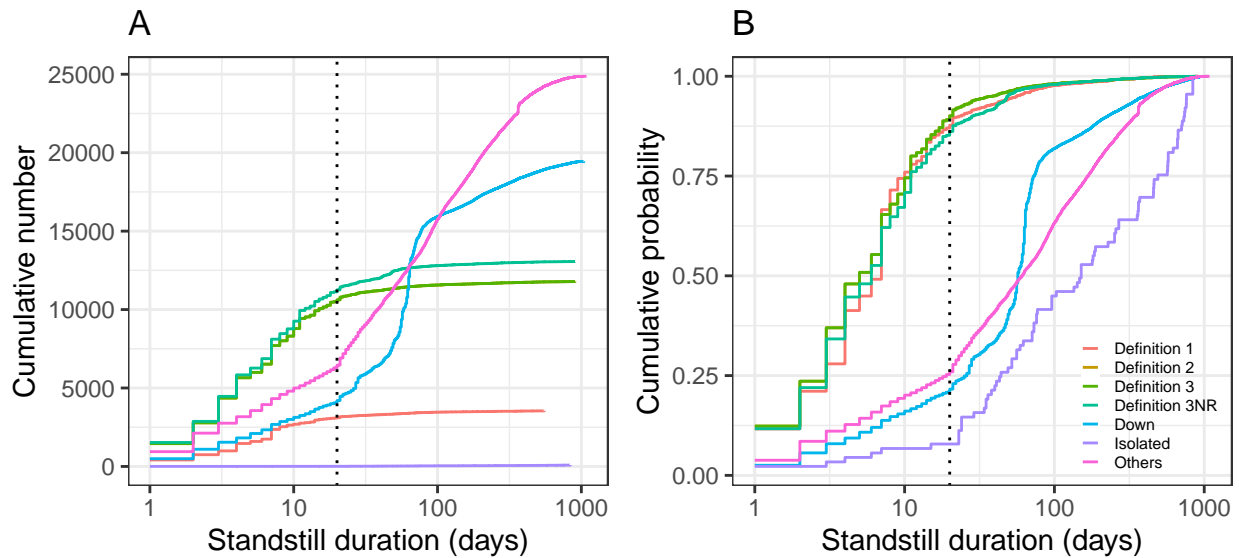


Figure 33: Distribution of movements as a function of their observed duration of standstill. A: Cumulative number of movements, B: Corresponding cumulative probability. Movements from several populations at risk were considered: movements occurring within breeding pyramids as defined by the considered pyramid definitions, movements from holdings outside pyramids but receiving pigs from T1, T2, T3 and T4 holdings (Down), movements from holdings outside pyramids receiving pigs from isolated T3 holdings (Isolated), and movements from holdings never in direct contacts with pyramids (Others)

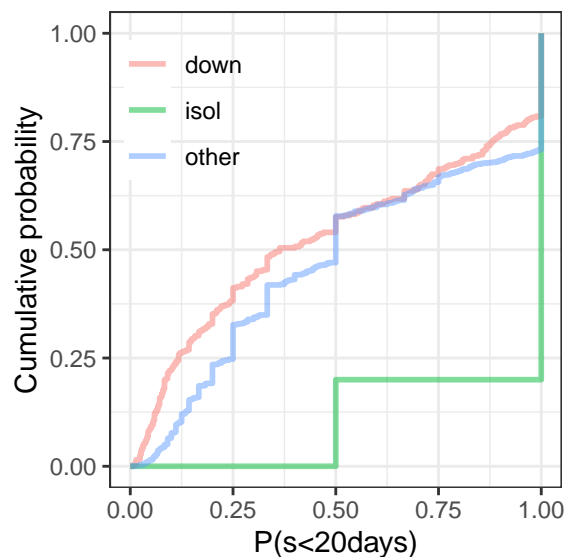


Figure 34: Cumulative distribution of the proportion of movements breaching standstill regulation for all holdings outside pyramids which showed at least one movement with a standstill of less than 20 days.

Table 6: Proportion of movements within statutory standstill periods for various population of holdings

	Mtot	MStot	%MS	n	%n
Within pyramids					
Definition 1	3543	3083	87.0	59	54.1
Definition 2	11786	10502	89.1	217	74.3
Definition 3	11787	10503	89.1	218	41.4
Definition 3NR	13064	11131	85.2	231	38.9
Outside pyramids					
Down	19442	4054	20.9	335	20.8
Isolated	89	7	7.9	5	6.3
Others	24873	6285	25.3	893	3.6
Reporting PRIMO movements					
Down	12818	2260	17.6	192	20.7
Isolated	67	4	6.0	4	6.8
Others	10892	3863	35.5	289	13.5

Note:

Mtot: Total number of movements. MStot: Total number of movements within statutory standstill periods. %MS: Proportion of movements within statutory standstill periods. n: Number of holdings with at least 1 movement within statutory standstill periods. %n: Proportion of holdings with at least 1 movement within statutory standstill periods. Here, the statutory standstill period is defined as a 20-day standstill period on any pigs on premises upon the arrival of any pigs onto premises.

Holdings reporting PRIMO movements are holdings from England or Wales involved in movements reportedly made under PRIMO in eAML2.

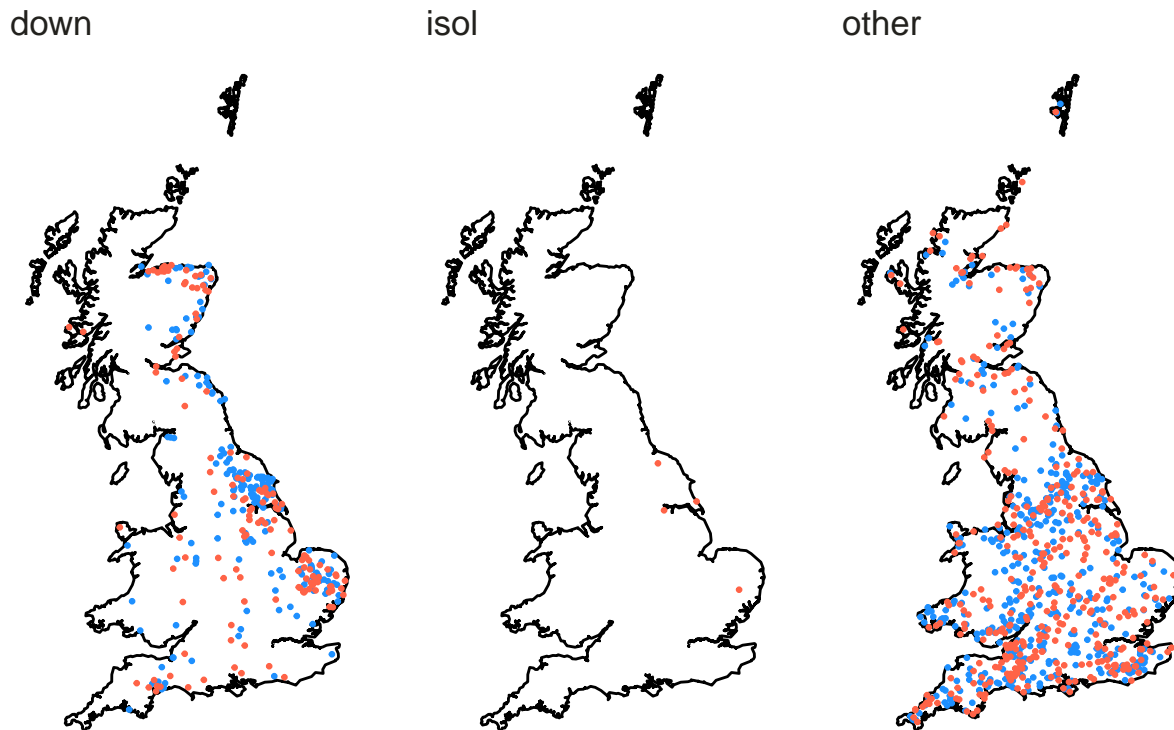


Figure 35: Maps showing the location of holdings outside pyramids which showed at least 1 movement (blue) or more than half of all movements (red) that appear to breach standstill regulations. Note that all locations were randomly jittered within 10km to ensure confidentiality of farm locations.

4.1 General observations

During the period 2016-2018, 19 registered pyramids were present in GB, which represents 7 less than during the 2012-2013 period. Altogether, 527 pig holdings were involved in these registered pyramids, among which 55.4% were approved by APHA under PRIMO. These registered pyramids represent a small proportion (1.7%) of all British pig farms as well as a small proportion (13%) of the 53,968,739 pigs that moved in GB during the 3-year study period.

As in the previous report, some of these pyramids, taken individually, showed large geographical coverage, with the three largest pyramids having farms located both in England and Scotland (Figure 11). This, by itself, could represent a high risk for widespread transmission of infectious disease in the industry given that moving pigs within pyramids does not trigger a standstill period (Figure 33B).

Registered pyramids were not isolated from the rest of the British pig industry, sending (and sometimes receiving) pigs from several holdings outside pyramids (Figure 15). These movements represent an important risk for infectious diseases to enter pyramids and spread over the entire industry, and require high standards in biosecurity as well as a 20-day standstill period. However, given the frequency of some of these movements, it would be unlikely that the statutory standstill period is respected. Furthermore, the level of biosecurity implemented in these farms remains unclear as they were typically not approved by APHA under PRIMO. Better understanding the reasons why pigs were traded with holdings from outside pyramids is then needed to ensure pyramids are properly isolated from the rest of the industry in GB.

Registered pyramids were also found regularly moving pigs between each other. When considering movement between holdings involved in pyramids alone, 13 pyramids among the 19 registered pyramids were found interconnected. Altogether, these 13 pyramids involved 91% of all holdings actively moving pigs within registered pyramids and covered a large area in GB (Figure 17). According to our results, cross-pyramid movements involved holdings from all tiers, either moving pigs down the production chain or to the same tier. In particular, we identified 35 holdings, including 2 in Scotland, that actively participated in cross-pyramid movements and were critical for the cohesion of this large component (Figure 19).

The purpose of cross-pyramid movements is likely to replace high value gilts or improve the genetics merit (i.e. the ability of a given animal, relative to others, to produce superior offspring) of the breeding animals in the receiving pyramids. It is therefore not surprising that most of the influential cross-pyramid holdings are Nucleus (10) or Grow-Out units (10). However, moving pigs across pyramids requires that a quarantine period is implemented in so-called 'isolator' units before mixing pigs with the rest of the herd. Although information on presence of an isolator unit in each approved holding is recorded in the database (Pers. com. Mark Rigby, APHA), such a record was not immediately available to EPIC. In absence of such records, we cannot say if cross-pyramid movements involved isolator units and that quarantine is properly implemented. Given their importance in interconnecting pyramids, this should be made clearer in the movement databases in both Scotland and England/Wales. At the minimum, efforts in (i) ensuring that quarantine and high biosecurity

standards are carried out in these holdings, as well as (ii) prioritising them for surveillance activities should be made to ensure pathogens are detected before entering into pyramids and avoid widespread transmission.

As mentioned above, registered pyramids are pyramids that involved at least one breeding unit that supplies pigs to one or more production pyramids. In this work, we found that some PRIMO-approved T3 holdings did not receive pigs from breeding pyramids. Instead, they either did not show incoming movements or received pigs from non-approved holdings. In all cases, these PRIMO-approved T3 holdings sent pigs directly to slaughter or to finishing holdings. Some of these finishing holdings met our criteria for T4 holdings and, therefore, formed what we called a *non-registered* (NR) pyramid, composed of T3 and T4 holdings. We believe that these NR pyramids represent small production pyramids but do not belong to major meat production companies. It is not clear, how genetic merit is preserved in these NR pyramids. Although they may receive replacement stock from farms outside GB, only few of the T3 holdings belonging to these NR pyramids showed records of movements from ferry ports. Instead, some T3 holdings received pigs from non-approved holdings. Not only it is doubtful that movements from non-approved holdings would enable T3 holdings to retain a high-enough level in genetic merit of their breeding population to meet their productivity needs, it is also inconsistent with the registration procedures for PRIMO-approved holdings.

None of these NR pyramids are isolated from the rest of the industry, since they not only receive pigs but also send pigs to non-approved holdings. It is difficult to know from movement records if non-approved holdings receiving pigs from NR holdings belong to the same business but, if they do, the role of businesses in production pyramids, and how these latter are defining pyramids, needs to be clarified. In particular, it would require a clear understanding of why some holdings of the same company were approved by APHA under PRIMO, whereas other were not. Alternatively, non-approved holdings receiving pigs from these NR pyramids might be butchers or meat packing plants, where pigs are slaughtered and processed on site, and for which activities were not clearly identified from their movement records. If this is true, the risk would be limited and may explain why most of these movements were reported as made under PRIMO. However, we do not have data listing these facilities to confirm this hypothesis. In this situation, we can only assume these holdings are farms.

Finally, using only records of PRIMO from 2017 to identify holdings involved in pyramids for the 3-year study period may have increased the likelihood that we missed PRIMO-approved holdings. Although this is a very likely explanation, yearly analysis of movement records would have highlighted changes in the pattern of movements from these holdings. Instead, we found that these movements consistently occurred throughout the three years of the study period. Nevertheless, if non-approved holdings sourcing pigs from NR pyramids truly belong to the same business, they most likely belong to a quality health assurance scheme (e.g. Red Tractor or QMS) and therefore would fulfil high biosecurity standards, mitigating the risk of disease spread. However, our findings highlight a need to better understand the role of businesses in these NR pyramids and clarify how these companies report their movements.

Over the list of all PRIMO-approved WB/WR holdings, 43 holdings were found to exclusively send pigs to

slaughterhouses and/or to non-approved holdings, with no records of contacts with holdings involved in pyramids, whether registered or non-registered. While none of the non-approved holdings trading pigs with these “isolated” T3 holdings met our criteria for T4 holdings, they were rarely involved in movements carried out within the 20-day statutory standstill period (Table 6). It is unlikely that these holdings are isolator units since they would show movements of animals from non-approved holdings as well as movements to PRIMO approved holdings. As such, these findings raise the question of why these isolated T3 holdings went through the process of being approved by APHA. Whether these holdings are registered through some legacy approval or whether they actually benefit from this procedure is unknown, however clarifying the purposes and reasons from such a status would be helpful to better evaluate risk and mitigate impact of disease control activities on their business.

Over the three-year study period, 32 WB/WR PRIMO-approved holdings did not show any records of movement. Although we analysed all movements reported to ScotEID and eAML2, it remains unclear why these PRIMO-approved holdings were not active. Although unlikely, a potential explanation is that movements may not have been reported to ScotEID and/or eAML2 but records were kept on farm instead. Also, issues in recording the data as well as during its processing cannot be ruled out to explain this finding. Nevertheless, if these 32 WB/WR holdings were truly not involved in moving pigs during the study period, strategies for outbreak response based on PRIMO-approved holdings would likely be affected, particularly by potentially misallocating resources to inactive farms.

4.2 Defining pyramids

In this work, we considered pyramids divided in four tiers, among which the two top tiers (T1/T2) represent a single breeding pyramid from which high genetic value pigs are sent to one or several production pyramids. Production pyramids are typically owned by a single meat production company and consist in at least one WB/WR holding (i.e. T3 holding) that breed pigs to be slaughtered or sent to dedicated finisher units (i.e. T4 holdings) to be fattened prior to slaughter (Figure 3). Such an integrated vertical production system is theoretically well defined and should be relatively easy to characterise and isolate. In GB, breeding pyramids are well identified and characterised, with the ‘Nucleus-Multiplier’ sheet database registering all breeding holdings belonging to the same breeding pyramid and for which biosecurity status is approved by APHA under PRIMO. For each given year, breeding holdings are then recorded with a pyramid identifier (i.e. *NM identifier number*), unique to each breeding pyramid. These *NM identifiers* allow holdings involved in each given breeding pyramid to be identified and their movement records can be easily extracted from the different available databases. In the previous report (EPIC 2016), we took advantages of these *NM identifiers* and limited our definition of pyramid to holdings belonging to the same breeding pyramid. This definition is similar to *Pyramid Definition 1* and represent a practical and accessible way to define pyramids. Yet, this definition ignores a large number of pigs moving between holdings of high biosecurity standards and belonging to the same production pyramid.

Several definitions of pyramids were then developed, with each definition progressively increasing the

number of tiers that were considered. These definitions were then used to better understand and characterise the structure and interconnections of pyramids as well as better understand the flow of pigs between holdings that can be affected by movement restrictions. In doing so, it was critical to identify which holdings, whether approved or not by APHA, belonged to each tier of each pyramid. However, this has proved difficult.

In contrast to farms involved in breeding pyramids, no unique identifier is used in databases to identify and individualise production pyramid. Likewise, the NM identifier of breeding pyramid(s) supplying pigs to production pyramids is not currently recorded, which, if available, would allow robust and rapid linkage between breeding and production pyramids. Instead, details of both name of owners and name of main sources of pigs, both pieces of information that are required as part of the approval procedures, are recorded as free text. Free-text information is prone to introduce misallocation errors (due to spelling errors, similarity of names or erroneous information) and was, thus, deemed impractical to characterise pyramids and connect production to breeding pyramids. We therefore identified T3 holdings belonging to a given pyramid based on downward movements of pigs from T1/T2 holdings as recorded by Scoteid and eAML2. In this work, we assumed that T3 holdings source pigs from a single breeding pyramid and allocated them to breeding pyramids if records of movements were present. As a consequence, a single movement from a T1/T2 holding was sufficient to allocate T3 holdings to a specific breeding pyramid. While this had the advantage of identifying all downward movements within each pyramid, it also highlighted that T3 holdings may receive pigs from multiple breeding pyramids. Here, we found that 43 T3 holdings were involved in multiple pyramids. We acknowledge that the network of movements was constructed over a 3-year period which, given the fact that production pyramids can switch suppliers mid-year (Mark Rigby, pers. comm. 2020), may overestimate the connectivity of holdings and bias our interpretations. However, constructing the network based on movements reported in each individual year of the study period did not change the network structure. This finding suggests that cross-pyramid movements are a common occurrence and a better understanding of the reasons would be key in identifying how to mitigate risk of cross-pyramid disease spread.

Finishing units are typically considered at a lower risk for disease spread since animals are theoretically sent exclusively to slaughter. However, finishing units, as any farms, are a good environment for pathogens to circulate and remain undetected for a considerable period of time. Notably, modelling work based on mortality records from nine commercial finishing herds of the Federation of Russia suggested that African swine fever could be circulating in a given herd for nearly a month before it causes a marked increase in mortality and infection being detected by surveillance activities during outbreak response (Guinat et al 2018). This is consistent with previous modelling work analysing the 2000 classical swine fever outbreak in GB (Gamado et al 2017). It is therefore important that finishing units involved in pyramids source pigs exclusively from PRIMO-approved holding and restrict movements to slaughter to limit opportunities for pathogens to spread undetected within pyramids. Based on these observations, not every finishing units sourcing pigs from pyramids can be considered as T4 holdings.

Because T4 holdings are most often owned by the same production company or are contractuated by

production company to finish pigs, the presence of a business relationships between holdings presents a possible way to define T4 holdings. Unfortunately, no centralised datasets exist recording business relationships of finishing units with breeding and/or production pyramids. Consequently, in this study, holdings belonging to the bottom tier of production pyramids could only be identified based on their movement records.

Based on discussions with the pig industry, several simple criteria were identified to define T4 holdings and discriminate those from finisher units that source pigs from pyramids but do NOT belong to any of them. Here, we considered a finishing holding as T4 holdings if: (i) they exclusively sent pigs to slaughter, either directly to slaughterhouse or through markets; (ii) they exclusively received pigs from PRIMO-approved holdings; and (iii) they had no movements recorded to or from a showground during the study period. We further relaxed these criteria by considering holdings showing records of movements from outside GB (i.e. through ferry ports) or showing records of movements for the purpose of disease surveillance and/or animal health (i.e. to APHA or SRUC veterinary surveillance centres or to veterinary clinics) to remain eligible to be included in T4. Although we believed these criteria were wide enough to ensure maximum inclusivity, most of the 1954 holdings receiving pigs from PRIMO-approved holdings were not considered part of a pyramid. In fact, 1143 (58%) farms sent pigs to non-approved holdings or to showgrounds, and 542 (28%) farms received pigs from non-approved holdings. These findings highlight that only a few finishing units receive pigs exclusively from production pyramids, and further strengthen the fact that pyramids are not as isolated from the rest of industry as theoretically believed.

As previously mentioned, pig holders in England and Wales have the opportunity to declare movements as made under PRIMO into the eAML2 movements database. This implies that non-approved holdings involved in movements made under PRIMO are involved in movements with PRIMO-approved holdings and, thus, should be considered as T4 holdings. These records may therefore represent a simple and quick alternative to identify T4 holdings. However less than 4% of non-approved holdings from England and Wales involved in PRIMO movements met our criteria to define T4 holdings. Beside the fact that this data would then be of limited use to define holdings involved in pyramids during or outside emergency response, it is critical to better understand reasons for such discrepancies. In reality, there may be reasons why individual movements occurred and declared as made under PRIMO. However, these were not recorded in the databases and, without further information, these findings should be viewed as an indication that there is some confusion in the regulations implemented in GB regarding movement licences. If this is true, efforts should be made to ensure owners and/or managers of finishing units clearly understand requirements of PRIMO and under what conditions movements can be declared as being made under PRIMO.

Nevertheless, movements of pigs to and from finishing units can be implemented if an appropriate 20-day standstill is respected to limit opportunities for virus to spread to other farms. When checking the duration of the standstill periods carried out by the 1954 holdings that directly received pigs from pyramids but did not meet our criteria (referred to as “Down” in this report), nearly a quarter of their movements occurred within the 20-days statutory standstill period. Although such a proportion is much lower than that observed for

holdings within pyramids, it remains concerning. The fact that 192/335 (57%) of the “Down” holdings moving pigs within the statutory period would declare movements as made under PRIMO, and that 168 of these 192 holdings will respect standstills for less than half the time, strengthen the argument that there is a lack of understanding of PRIMO and what is permitted under the order.

4.3 Movement restrictions and licences

Although PRIMO-approved holdings represent less than 1.2% of the overall number of pig holdings in GB, pigs produced in these farms are of high importance to the commercial sector. PRIMO-approved holdings, particularly those involved in breeding pyramids (i.e. T1/T2 holdings), are required to maximise the genetic merit of the pig population to increase the productivity of production pyramids. Keeping the flow of animals within and between tiers of pyramids is critical for the flow of genetic merit of the pig population at commercial level. Disturbing the flow of animal within pyramids would have a major long-term economic impact on production, potentially affecting businesses over several years.

Restricting the flow of pigs within pyramids would also affect the capacity of commercial farms to hold onto pigs beyond planned weights/ages (Andy McGowan, Scottish Pig Producers Ltd, pers. comm.). Such a restriction could rapidly generate welfare issues and necessitate culling of animals prior to intended weights/ages. Because non-commercial farms are more likely to involve outdoor production systems with low density stocking rates (Gillespie et al. 2015; Correia-Gomes et al. 2017), these producers have the capacity to retain their pigs for longer periods on their farms if necessary, so are less likely to incur welfare problems. Commercial producers are therefore most vulnerable in the face of movement restrictions. These reasons justify efforts to limit the consequences of movement restrictions on holdings involved in pyramids during outbreaks.

To limit the animal welfare and economic consequences of movement restrictions, one option is to provide derogations to small-distance movements between holdings of higher biosecurity standards and belonging to the same pyramid. If the authorised distance is small enough, these derogations were believed to limit the risk of widespread transmission while protecting the core of the industry from welfare issues. In this study, we found that the least restrictive strategy, among all scenarios of pyramid definition and distance that were considered, would be to provide licences to movements of <50km that occurred between all tiers (T1 to T4) of the same pyramid (including NR pyramids). Such a strategy will allow ~65% of the pigs that were expected to move within pyramids to travel to their destination, whereas derogation for movements of <10km, <20km would only enable 20% and 33% of the pigs to reach their destination, respectively. At the same time, restricting movements of >50km would markedly limit the number of trade connections between holdings, only allowing 35% of the trade routes to proceed. Despite these, more than half of holdings from each tier would still be able to move pigs. In the situation where an incursion occurs, this strategy seems to provide opportunities for pigs to flow between holdings while avoiding spread of disease over the entire pyramids.

However, the impact of restricting movements of >50km appears to differ between tiers. Production

pyramids would clearly benefit from it as most trade routes between T3 holdings and from T3 to T4 holdings would remain active, thereby lessening the impact on welfare and ensuring business continuity. In contrast, 67% and 84% of trade connections from T1/T2 holdings to T3 holdings and to T4 holdings would be stopped, respectively, because these premises are often more widely geographically distributed. This would have a dual effect on breeding pyramids. Firstly, it will limit the transfer of piglets of lesser genetic merit to finishing units to be slaughtered, adding pressure on the capacity of T1/T2 holdings to keep piglets on farm until movements to finisher units are permitted. Given the frequency of production in breeding farms, it is almost certain that welfare issues will arise very rapidly and that a decision to send pigs directly to slaughter (if permitted) would be taken despite the resulting significant economic losses. Secondly, these restrictions would disturb the flow of genetic merit from breeding to production pyramids. This latter may impact pyramids the most, as it will not only limit their ability to move replacement breeding stock (i.e. gilts and boars) to T3 holdings, thus affecting the genetic merit of the production pyramid, but also reduce the ability of T1/T2 holdings to effectively select animals of high genetic merit due to space constraints. In the situation that restrictions are enforced for several weeks, and despite the implementation of movement derogations, the average genetic merit of pigs within pyramids will likely depreciate and thereby have long-term effects on farms' productivity.

Nevertheless, restricting movements of >50km within pyramids will only have a marginal effect on the entire pig industry, allowing, on average, <6% of the total number of pigs moving between holdings within GB, irrespective of the length of time within which movement restrictions are enforced. In the situation where restrictions are enforced for 12 weeks, only 132,424 pigs would be allowed to move. This is not surprising knowing that within-pyramids movements represent only ~9% of non-slaughter pig trade in GB. Given that half of the non-slaughter pigs and nearly 80% of the slaughter pigs moved from holdings outside pyramids, representing an average of 91,367 and 139,596 pigs per week, respectively, the losses, both on economic and animal welfare standpoints, from restricting all movement outside pyramids will most likely dwarf all benefits that may result from derogations within-pyramids.

5 Conclusions & recommendations

This study highlights that the structure of the pig industry in GB between 2016 and 2018 is more complex than the theoretical top-to-bottom structure of vertically integrated pig production companies, and is smaller (i.e. less breeding pyramids) to what was found during the 2012-2013 period. There was a high level of interconnection between production pyramids that is misaligned with their use as a basis for compartmentalisation during outbreak response. Furthermore, movement regulations based on production pyramids may not be as effective as expected in order to prevent and control the spread of infectious disease or protect the industry as a whole. Efforts to improve registration and database structure are recommended if production pyramids are to be used for modulating disease control responses.

In addition, this work produced three key findings that may have implications for policy:

1. This work highlighted the need to electronically collect and centralise information on PRIMO approved premises, in a way that is easily accessible and can be linked to other databases. In the current format, it would be very difficult to use these data quickly, in response to disease incursion. It is recommended that consultations with all actors involved in assessing and recording PRIMO-approved farms should be carried out to identify ways for improving the system. In particular, we recommend that:

- A unique identifier for production pyramids should be generated by APHA during the registration procedures of holdings under PRIMO. This identifier need to be used consistently over time to ensure that all holdings belonging to production pyramids are easily and quickly identified;
- Both NM identifier and CPH identifier of the main and secondary source of pigs should be consistently recorded, separately to their name and address, during the approval process of PRIMO-approved holdings to ensure consistent and robust linkability of records across multiple databases. Overall, free-text records need to be avoided during registration procedures.
- The CPH identifier of all finishing holdings sourcing pigs from production and breeding pyramids should be declared during yearly approval procedure of PRIMO-approved holdings. At the same time, contracted finishing holdings should declare the CPH identifier of all holdings from which they source pigs.
- Details of all PRIMO-approved holdings, whether they are breeding units or WB/WR units, should be recorded in a unique, centralised database to simplify linkage with movement databases. In this register, the presence and capacity of isolation units should be recorded.
- Work needs to be carried out to better understand the trading behaviour of holdings involved in cross-pyramid movements. In particular, we need to understand the purpose of these movements and steps implemented to ensure safe and biosecure movement of pigs.
- Work needs to be carried out to better understand trading behaviour of finishing units to understand reasons behind departure from our criteria.
- Work needs to be carried out to clarify the rationales for farms in England and Wales to report movements as made under PRIMO.
- We need to understand motivations from owners and managers of PRIMO-approved holdings for registering with APHA under PRIMO.
- We need to enhance communication and training programmes targeting the commercial pig sector to raise awareness of PRIMO requirements and ensure proper recording.

2. Based on the evidence presented in this report, allowing only movements of <20km within pyramids is likely to offer little benefit to reduce the welfare impact of additional movement restriction on the industry when facing an outbreak of infectious disease. Concomitantly, expanding derogations to movement of <50km occurring between holdings of all tiers, from breeding to finishing and including NR pyramids, may have more value than the number of movements suggest, by limiting disturbances of the breeding cycle of animals of high genetic value.

3. Pyramids cannot be used as a basis for compartmentalising the pig industry, in an attempt to limit economic and animal welfare consequences of an outbreak of infectious diseases in the country, without significant efforts being made to ensure production pyramids are properly isolated from each other and from the rest of the industry. In particular, cross-pyramids movements should be avoided or should, at least, present records confirming that high biosecurity standards were implemented.

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