



Egocentric characterisation of the swine trade network in Cambodia and implications for disease surveillance and control

William T.M. Leung^{a,b,*}, Guillaume Fournié^{b,c,d}, Phalla Miech^e, Ty Chhay^e, Arata Hidano^a, Hannah Holt^a, Sina Vor^e, Sokchea Huy^e, Son Pov^e, Sothyra Tum^f, Monidarin Chou^g, Yvonne C.F. Su^h, Gavin J.D. Smith^h, James W. Rudge^{a,i}

^a Communicable Diseases Policy Research Group, Department of Global Health and Development, London School of Hygiene & Tropical Medicine, London, United Kingdom

^b Veterinary Epidemiology, Economics and Public Health Group, Pathobiology and Population Sciences Department, Royal Veterinary College, London, United Kingdom

^c Université de Lyon, INRAE, UMR EPIA, VetAgro Sup, Marcy l'Etoile, France

^d Université Clermont Auvergne, INRAE, UMR EPIA, VetAgro Sup, Saint Genes Champanelle, France

^e Livestock Development for Community Livelihood Organization, Phnom Penh, Cambodia

^f National Animal Health and Production Research Institute, General Directorate of Animal Health and Production, Phnom Penh, Cambodia

^g University of Health Sciences, Phnom Penh, Cambodia

^h Programme in Emerging Infectious Diseases, Duke-NUS Medical School, Singapore

ⁱ Faculty of Public Health, Mahidol University, Bangkok, Thailand

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ABSTRACT

Across Southeast Asia, enhanced characterisation of pig value chains is needed to understand disease risk pathways and inform control and surveillance strategies. This study defined a typology of value chain actors in Cambodia and characterised their individual, 'egocentric', swine trade networks. Questionnaire-based cross-sectional surveys were conducted between May 2020 and April 2022 in four south-central provinces, sampling 'egos' via a multi-stage cluster design. We describe networks of 376 egos involving 4705 trade partners ('alters') and 669,363 pigs over six months.

Five producer types were identified: company-affiliated large breeding (n = 21) and growing farms (n = 68), independent breeding- (n = 104) and growing-oriented smallholders (n = 77), and boar service providers (BSP; n = 19). Three pig-exchanger types were also identified: 'traders' (n = 11), 'middlemen' (n = 12), and 'butchers' (n = 51).

Network analysis revealed BSP, middlemen, and large breeding farms as 'brokers' with many in- and outgoing trade links with producers, increasing their potential for pathogen introduction and onward transmission. Logistic regression supported this risk-profiling: compared to breeding-oriented smallholders, BSP had 8.1 times greater odds (95% CI: 2.4–27.8) of high pig mortality risk ($\geq 5\%$ of herd size), while large breeding farms had 6.0 times greater odds (95% CI: 2.0–18.6) than large growing farms. Large breeding farms supplied pigs to all producer types including smallholders and BSPs (1% of their aggregate supply), underscoring their dissemination potential. Middlemen and BSP connected otherwise weakly connected smallholders, highlighting opportunities for targeted disease-control. Slaughterhouses acted as network 'sinks', receiving pigs from smallholders and farms associated with different companies, making them key targets for disease surveillance. Large farms transported pigs the furthest distances (median >40 km; max >120 km) while smallholders mostly traded pigs locally (median <5 km; max 114 km).

This study demonstrates the value of egocentric sampling for livestock network characterisation and contributes to the limited knowledgebase on swine trade networks in Southeast Asia.

Abbreviations: BSP, boar service provider; ODK, open data kit; FAMD, factor analysis of mixed data; HCA, hierarchical cluster analysis; SEA, Southeast Asia.

* Corresponding author at: Communicable Diseases Policy Research Group, Department of Global Health and Development, London School of Hygiene & Tropical Medicine, London, United Kingdom.

E-mail address: will.leung@wvs.org.uk (W.T.M. Leung).

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1. Introduction

Swine production is an important and evolving industry in Southeast Asia (SEA). The region accounted for 7% of global pig production in 2021, while pigs represented the largest source of meat by mass in Vietnam, Cambodia, Laos, and Timor-Leste (Ritchie et al., 2019; FAO, 2021). Alongside increasingly industrialised production in the region (Deka et al., 2014; Mason-D'Croz et al., 2022; Thai, 2018; Thanapongtharm et al., 2016), smallholder production remains widespread and supports rural livelihoods, food security, and socio-cultural roles (Alawneh et al., 2014; Borin and Henrichs, 2012; Christie, 2007; Deka et al., 2014; Huynh et al., 2006; Samkol et al., 2006). In Cambodia, for example, smallholders mainly raise pigs for sale, providing supplementary income and savings for households lacking formal banking (Osber et al., 2015; Ström et al., 2017; Tornimbene and Drew, 2012; National Institute of Statistics, 2021).

Over the past two decades, the region has experienced recurrent outbreaks of transboundary swine diseases (Kedkovid et al., 2020; Na Ayudhya et al., 2012). Notably, since its incursion into China in 2018, African swine fever (ASF) has been reported across all countries in SEA except Brunei (FAO, 2024), causing severe economic losses and trade disruptions (Berthe, 2020; Weaver and Habib, 2020). Beyond production impacts, pigs are also important reservoirs for zoonotic pathogens such as influenza A viruses (IAV) and play an important role in generating novel reassortant subtypes with pandemic potential (Huynh et al., 2006; Trevenne et al., 2011; Nelson and Worobey, 2018).

Consequently, there is a need for cost-effective, context-appropriate disease monitoring and control strategies. Understanding livestock trade networks can help inform such activities by identifying highly connected nodes important for disease transmission (Craft, 2015; Dubé et al., 2011; Martínez-López et al., 2009). However, swine trade networks remain under-characterised in SEA (ACIAR, 2012; Kalpravidh and Holley, 2019). Routine recording of swine movements in industrialised sectors has enabled network characterisation in Europe, North America, and recently Thailand (Bigras-Poulin et al., 2007; Buttner et al., 2013; Dorjee et al., 2013; Martínez-López et al., 2009; Noremark et al., 2011; Rautureau et al., 2012; Smith et al., 2013; Thakur et al., 2014; Wiratsudakul et al., 2022). Contrastingly, in smallholder dominated sectors, informal livestock movements limit the feasibility of this approach (ACIAR, 2012; Chaters et al., 2019).

Targeted network surveys have instead been used to characterise swine trade in some SEA countries (Baudon et al., 2017a; Poolkhet et al., 2019). These typically adopt 'link-tracing' or 'egocentric' designs. Link-tracing surveys sample networks through successive contact nominations revealing network structure but necessitating contact identification and follow-up which can be unfeasible (Baudon et al., 2017) and raises privacy concerns (Lindström et al., 2013; Moon et al., 2019; Wiltshire et al., 2019). Contrastingly, egocentric surveys collect information on 'egos', their trade partners, 'alters', and sometimes alter-alter ties. Despite yielding less structural information, they do not require unique contact identification or follow-up and can adopt probability-based sampling, facilitating integrated data collection efforts (Morris and IUSSP, 2004; Robins, 2015).

In Cambodia, limited data on swine movements hinders effective disease monitoring and control. Previous value chain mapping exercises have described swine production and trade flows in aggregate (Borin and Henrichs, 2012; Gross, 2019; Ly, 2016; Tornimbene and Drew, 2012) but a quantitative characterisation of the trade network remains lacking. Infectious disease remains a major constraint to pig production (Huynh et al., 2006; Ström et al., 2017), yet livestock diseases surveillance remains limited and reliant on external funding (Goutard et al., 2015; Siengsan-Lamont et al., 2022). These challenges are compounded by the predominance of smallholders who often have limited access to veterinary services, low awareness of disease prevention, and are associated with informal live pig trade (ACIAR, 2012; Huynh et al., 2006; Osber et al., 2015).

To address these challenges, we conducted an egocentric survey of live pig trade in Cambodia as part of the 'PigFluCam+' project investigating zoonotic risks from pig rearing systems. Our objectives were to (1) generate an updated, data-driven typology of value chain actors; (2) characterise the egocentric networks of value chain actors and describe swine movement pathways among them; and (3) demonstrate the use of egocentric sampling methods for livestock network characterisation.

2. Methods

2.1. Study design

2.1.1. Study overview

A questionnaire-based, cross-sectional survey was conducted in Cambodia from May 2020 to April 2022. The survey spanned a two-year period due to COVID-19-related travel restrictions which necessitated pauses in fieldwork activities (Figure S 1). The survey aimed to collect data on value chain actor characteristics and practices relating to swine production, management and trade. Specifically, interviewees ('egos') were asked to provide information on trade partners ('alters') with whom they had exchanged pigs with within a set timeframe. No alter-alter ties were recorded. The study design can therefore be described as a 'star egocentric network' survey (Almquist, 2012) which we refer to as 'egocentric' throughout.

2.2. Study area and population

The study was conducted in south-central Cambodia; specifically, within Phnom Penh autonomous municipality (containing the capital city, Phnom Penh) and three surrounding provinces: Kandal, Kampong Speu, and Takeo (Fig. 1). This study area was selected due to the high density of pigs in this region, the diversity of pig production types represented, and for accessibility to field teams in Phnom Penh.

The study population comprised value chain actors (henceforth, 'actors') involved in the raising, transport, or slaughter of live pigs as defined in Table 1. Actors could therefore be sites (e.g. farms or slaughterhouses) or people (e.g. pig traders). The actor types used for sampling were informed by previous value chain analyses and mapping exercises of the Cambodian swine sector (Borin and Henrichs, 2012; Gross, 2019; Ly, 2016; Tornimbene and Drew, 2012).

2.3. Sampling design

The network survey adopted a similar sampling scheme to two other studies within the 'PigFluCam+' project: a cohort study of influenza A virus (IAV) in occupational swine workers, and slaughterhouse surveillance of IAVs in swine (Zeller et al., 2023). Therefore, the sampling design was balanced to meet the objectives of these interlinked studies.

Actors were sampled via a stratified, multi-stage cluster-based design with some adaptations to accommodate varying data availability. Sampling strata and clusters were based, respectively, on value chain actor types and geographic (administrative) areas. First, in each purposively selected province and Phnom Penh municipality (primary sampling units), two districts (secondary sampling units) were selected with probability proportional to pig population size, used as a proxy for the number of value chain actors due to a lack of data on actor distributions by geographical unit. Within each district, sampling frames for each actor type were compiled through consultation with provincial and district veterinary offices and Cambodia's National Animal Health and Production Research Institute (NAHPRI), utilising existing actor registration requirements (Table 1). Further details on actor-specific sampling approaches are provided in Supplementary Information 2, with sampling frequencies listed in Table 1.

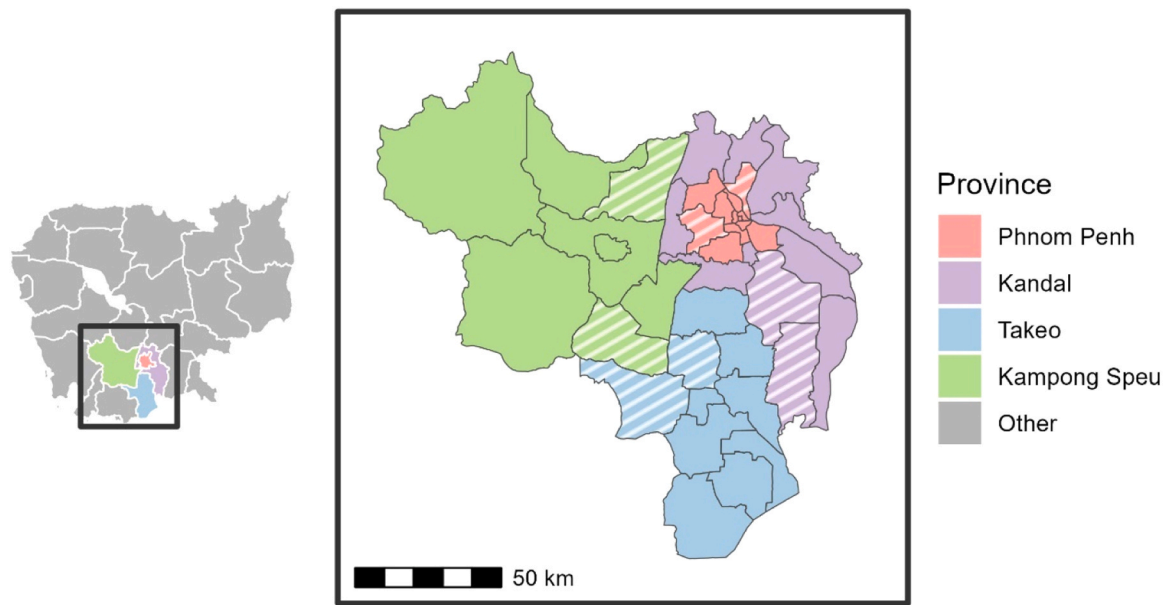


Fig. 1. Study area: Panels show the map of Cambodia (left) and the study area (right) showing the three study provinces and Phnom Penh autonomous municipality (coloured) and selected study districts (striped).

2.4. Data collection and management

2.4.1. Questionnaires and field surveys

Structured questionnaires were developed for: 1) pig producers (i.e. [semi-]commercial farms, smallholder producers, and boar service providers [BSP]), 2) pig exchangers, and 3) slaughterhouses. Questions were mostly closed-ended and were related to: actor demographics, site/herd management practices, pig health, and pig trading practices (described in the next section). For producers, the implementation of a predefined set of on-site biosecurity measures was also recorded (Table S 1). Biosecurity measures implemented and number and types of pigs kept were cross-checked by interviewer observation where possible. Questionnaires were developed in English and translated to Khmer – the language used during interviews. To confirm translation accuracy, back-translations were performed by an independent agency.

Data collection was conducted by the London School of Hygiene and Tropical Medicine and Livestock Development for Community Livelihood Organization. Field enumerators participated in training workshops to review questionnaire content and data entry and informed consent procedures. Questionnaires were also pre-tested in field settings to screen for any errors in the forms and to assess the applicability and clarity of questions with respondents. Most interviews were conducted face-to-face but a minority were via phone due to the COVID-19 pandemic ($n = 8$; 4 pig exchangers and 4 BSP). Data were recorded using Open Data Kit (ODK) (Hartung et al., 2010) installed on tablet computers.

2.4.2. Description of egocentric network data

To facilitate internal data validation and to reduce recall bias, egos were asked to report their alters first in aggregate, and then individually. This helped to identify data entry errors and minimise omissions of individually reported alters due to respondent and/or interviewer fatigue (e.g. see Eagle and Proeschold-Bell, 2015; Klodahl, 1985; Perry et al., 2018). In aggregate, we recorded: 1) the number of alters of each actor type with whom egos had exchanged pigs within a set timeframe, and 2) the number of pigs exchanged for each pig type (e.g. piglets, weaners, growers, finishers, boars – hired or purchased, and sows). At individual-level, we recorded: 1) alter type, 2) relationship with the alter (e.g. contract, family, none), 3) alter location (i.e. smallest known administrative division), 4) whether they had traded pigs with the alter

before, and if so, the typical transaction frequency, 5) number of pigs of each type sent by/received from this alter, and 6) contact details (recorded for recruitment purposes). If the alter was a pig exchanger, further questions were asked about the ultimate origin or destination of pigs (e.g. location and actor type).

Egos were asked to report all alters with whom they had traded live pigs during a defined 'recall period'. Based on questionnaire pre-testing, the time-frame of the recall period was carefully balanced to maximise data capture while minimising respondent burden and maintaining data reliability. A 6-month recall period was used for producers to capture at least one production cycle, while a 14-day period was applied to pig exchangers and BSPs due to their frequent trading. For slaughterhouses, a 7-day recall was used as their alters remained relatively consistent over time. This approach was used over alter-truncation (i.e. limiting the number of reported alters) to minimise biases such as from saliency (e.g. reporting the most frequently traded alters first) and order effects (e.g. reporting similar alters consecutively) (Perry et al., 2018). For analyses comparing distributions of degree, transactions, and strength among actors, egocentric networks were standardised to equal recall periods (see Section 2.4.2). A summary of the measures taken to mitigate anticipated errors and selection- and information-biases are presented in Table S2.

Slaughterhouses, pig exchangers, and BSP were asked whether the numbers of pigs they traded varied over the year to assess potential seasonal variations. Egos were asked to report periods during which the number of traded pigs was the highest and the lowest.

2.4.3. Data management and validation

Completed questionnaires were sent to an ODK Aggregate server. Pig trading data were checked for errors and internally validated through comparison of aggregated and individually recorded data – specifically, comparing the total numbers and types of pigs purchased and sold, and numbers and types of actors involved. Inconsistencies were addressed through consulting with field teams and by checking field notes (detailed in Section 3.1).

2.5. Actor typology generation

To generate an updated, data-driven typology of these actors based on their pig production and trading practices, we applied a two-step

Table 1

Sampling overview: Value chain actor types used for sampling and their definitions, data sources used for sampling frames, and cluster sampling units (CSU) from which actors were recruited (i.e. the smallest CSU for each actor type in a multi-stage design). The number of egos recruited is also shown along with the total number of alters that they reported for a given type. N.B. alters do not necessarily represent unique value chain actors. *Indicates actors that were sampled via respondent driven sampling: Boar service providers (n = 4) and unregistered pig exchangers (n = 4).

Value chain actor types used for sampling	Definition Data sources	Cluster sampling unit	Egos n (%)	Alters n (%)
(Semi-) Commercial farm	Semi-commercial or commercial pig producer raising ≥ 50 pigs. <i>Census in selected districts provided by provincial authorities.</i>	Districts	89 (23.5)	133 (12.1)
Smallholder producer	An individually / family-owned pig production site raising < 50 pigs. <i>Census in selected villages provided by district and village authorities and updated through observations during field visits.</i>	Villages	181 (47.8)	491 (44.6)
Boar service provider (BSP)*	Smallholder producers providing a paid service for the hire of boars for breeding. N/A	Provinces	19 (5.0)	102 (9.3)
Pig exchanger (registered)	Actors who purchase live pigs and sell pigs or carcasses/pig meat to other actors as a form of business. They are licensed to transport pigs and/or sell meat. <i>Permits and licenses for transporting/moving livestock; or for selling carcasses, held by district authorities.</i>	Districts	66 (17.4)	298 (27.1)
Pig exchanger (un-registered)*	As above but unlicensed. N/A	Provinces	8 (2.1)	
Slaughterhouse	A registered site in which pigs are killed. <i>Permits required for their operation, held by the Department of Animal Production and Health (DAPH) or the Provincial Department of Agriculture.</i>	Districts	16 (4.2)	77 (7.0)
Totals			379 (100)	1101 (100)

multivariate analysis combining dimensionality reduction and hierarchical clustering analysis. Analyses were conducted separately for producers and pig exchangers and resulting actor types were used – along with slaughterhouses – in all subsequent analyses unless otherwise stated.

First, factor analysis of mixed data (FAMD) was used to reduce select

categorical and numeric variables into smaller sets of synthetic uncorrelated dimensions or ‘principle components’ (PCs), with the first PC capturing the largest fraction of variance and successive components accounting for progressively less (Husson et al., 2017). The producer FAMD considered 51 variables related to site ownership, types and number of pigs raised, herd management, pig trading activity, and biosecurity (Table S3). Fourteen growing farms – commonly kept empty between batches – had no pigs at the time of visit so farm size was imputed by taking the mean farm size reported by producers with a similar production type and (where relevant) company affiliation. The pig exchanger FAMD considered 22 variables related to pig trading (Table S 4).

Next, based on the FAMD component values, hierarchical clustering analysis (HCA) was applied to identify actor clusters. The number of components used for this analysis was based on identifying an ‘elbow’ on the scree-graph following standard methods (Jolliffe, 2002). We employed Ward’s method using Euclidean distance to assess the level of dissimilarity between actors followed by K-means consolidation. The number of clusters was selected based on a drop in inertia (Husson et al., 2017). All FAMD and HCA analyses were conducted in R software (version 4.2.0) (R Core Team, 2020) using the FactoMineR package (Lé et al., 2008).

2.6. Egocentric network analysis

2.6.1. Network analysis

In the egocentric networks, nodes represented value chain actors, and edges were pig trades or transfers among actors. Edges were directed and weighted by the number of pigs traded among two nodes. They were defined as ‘terminal’ if they led to pig slaughter or ‘non-terminal’ if not.

The following measures of node-level network connectivity were calculated for egos: the number of alters that an ego purchased pigs from (in-degree) and sold pigs to (out-degree), the total number of pigs they purchased (in-strength) and sold (out-strength), and the total number of transactions for purchases (in-transactions) and sales (out-transactions). Lent boars, which were by definition returned to their farm of origin after a given time, generated reciprocated edges. Therefore, these movements were included in both in- and out-network measures. Geographic Euclidean distances between egos and alters were also computed whereby alter locations were the centroid of the smallest reported administrative area to which they were associated.

Alters were reclassified for consistency with the ego types generated above (detailed in Supplementary Information 3). For each ego type in aggregate, the total number of suppliers and recipients of each alter type was then quantified, as was the total number of pigs the egos traded with this alter type. Pig movement pathways among actor types were visualised using directed unweighted networks in which each actor type was a node, and any trade of pigs between actors of two given types, was an edge. Plots were generated using the R package: ggraph (Pedersen, 2023) with minor formatting edits made in Inkscape (version 1.2.1).

2.6.2. Egocentric network rescaling

For analyses comparing distributions of degree, transactions, and strength across actor types, egocentric networks for slaughterhouses (7-day recall), pig exchangers, and BSPs (14-day recall) were rescaled to 6-months, i.e., the recall period used for producers. This scaling standardised and made transparent, calculations that may otherwise be required in field settings during cross-sectional network surveys. For example, estimating the number of pigs traded by multiplying average batch size by transaction count.

We made the simplifying assumption that a sampled egocentric network was representative in terms of ego-level (in- and out-) degree and strength, i.e. that these metrics were stable over time. The general principles for rescaling egocentric networks were as follows (see Supplementary Information 4 for pseudocode and detailed description).

When egos made repeat trades with an alter during the surveyed recall period (e.g. daily trades; 14-days recall), degree remained unadjusted but the observed number of pigs traded with that alter was weighted by the ratio between 6 months and the recall period. When an ego made only one transaction with an alter during the surveyed recall period (e.g. monthly or yearly trades; 14-days recall), both degree and strength were adjusted by weighting. In practice, this was achieved by imputing additional alters with identical features to the sampled set of alters, such that degree was maintained for each unsampled time period. The number of transactions an ego made with each (sampled and imputed) alter in a 6 month period was then calculated by dividing 6 months by the transaction frequency.

2.7. Risk factors for pig mortality

We investigated the association between producer type (the single independent variable) and self-reported pig mortality risk using univariable logistic regression models. The binary outcome was defined as a mortality risk of $\geq 5\%$ of the current herd size in the previous 6 months, chosen over morbidity risk due to its reduced subjectivity. Analyses were conducted separately for smallholders and commercial farms to account for the considerable differences between these producer types.

Herd size was not adjusted for as this variable was used in the producer typology construction. Network metrics (e.g. in-degree, in-transactions, in-strength), although not used in the typology generation, were not adjusted for as they were colinear with producer type and were considered to be on the causal pathway between producer type and the outcome. For example, specialisation was expected to mediate the number of inward transactions a producer had (e.g. with the replacement of sows in breeding units likely to generate more transactions compared to growing units), which could in turn influence the chances of disease introduction and hence mortality risk.

3. Results

3.1. Recruitment, network rescaling, data cleaning and validation

Overall, 379 egos were interviewed and provided information on their transactions with 1101 alters involving 542,377 pigs (Table 1). Sixteen (9%) smallholders also reported using artificial insemination doses from BSP, however, these were not considered in the network analysis which focused on live pig exchanges. Alters for whom locations were known ($n = 874$; 79%) were distributed in 9 of the 25 Cambodian provinces (Takeo [40.5%], Kampong Speu [24.8%], Kandal [23.9%], Phnom Penh [3.6%], Kampong Cham [0.1%], Kampong Chhnang [0.1%], Pursat [0.1%], Preah Sihanouk [0.1%]). Commercial farms were able to report the locations of only 32 (16%) of their alters. Of the pig exchanger alters reported by producers, the production origins or ultimate destinations of traded pigs was known for less than half ($n = 52$; 44%). Inconsistencies between aggregate and individual trade data were identified for 29 alters (3%) (see Supplementary Information 5 for inconsistency types and how they were addressed).

In the 6-month rescaled networks used to compare distributions of degree, transactions, and strength, the 379 egos traded with an estimated 4705 alters involving 669,363 pigs. The majority of the increase in alters (62%) was attributable to BSP and can be explained by short survey recall periods (14 days) in combination with their high degree, and infrequent repeat trades.

3.2. Actor typologies

3.2.1. Producer typology

Producer typology construction was based on two FAMM components explaining 32% of the data variability (PC1 = 25%; PC2 = 7%; Figure S2). Hierarchical clustering grouped producers by farming system (i.e. smallholders vs. farms) and production stage (breeding vs.

growing). This included two commercial farms (Table S5): large breeding farms (FB; $n = 21$) and large growing farms (FG; $n = 68$) – which were company contracted or owned, had high biosecurity (e.g. $>90\%$ adoption of measures in Table S1, except mosquito net use), and chiefly ($>85\%$) operated all-in-all-out systems by room (i.e. pigs went through production stages in groups). The remaining types were independently-owned smallholders (Table S5). BSP initially clustered with breeding-oriented smallholders, but were analysed separately due to our specific interest in understanding their position in the network, resulting in three types: BSP ($n = 19$), breeding-oriented smallholders (SB; $n = 104$), and growing growing-oriented smallholders (SG; $n = 77$). Production specialisations of SB and SG were less clearly delineated compared to FG and FB. Nearly all smallholders (99%) had under 100 pigs, consistent with Cambodia's official classification threshold (MAFF, 2018; the previous threshold – used at recruitment – being 50 pigs) (Fig. 2). Boars were kept by all BSP, but were uncommon in SB (5%) and SG (3%). Smallholders had relatively low biosecurity levels, with most biosecurity measures in Table S1 being adopted by under 50% of smallholders, and 40% of SB and 10% of SG adopting none. Mosquito net use was an exception, having relatively high adoption rates ($>50\%$). Swill feeding was also common (62%). Among smallholders, BSP reported the highest levels of vaccination adoption (95%) and disinfection frequencies (63% on a weekly basis) (Table S5).

3.2.2. Pig exchanger typology

The typology for pig exchangers was based on three components explaining 55.3% of the variation in the dataset (PC1 = 27.3%; PC2 = 18.1%; PC3 = 9.9%; Figure S3). Three clusters broadly separated these actors according to the production stages and volumes of pigs traded (Table S6). Middlemen (Mi; $n = 12$) exclusively traded weaners, mostly transferring pigs among smallholders, and used a moped/motorbike (83%). Traders (Tr; $n = 11$) traded terminal pigs (i.e. sows and finishers) in large volumes (median 120; range 14–600 pigs in 14 days), mostly using four-wheeled vehicles (82%). All traded with companies (100%) – with only two traders (17%) purchasing pigs from more than one company in their surveyed period. Butchers (Bu; $n = 51$) received pigs for slaughter, rarely traded them onward (4%), and half transported pigs (51%). Pig exchangers did not cluster completely according to their licensure (Table S6). Pig exchangers often entered pig pens or houses to load and unload pigs, with over 30% of Mi, Tr, and Bu always doing so. Most traders (82%) and butchers (69%) never collected pigs from multiple sites in a single trip, and 73% and 80%, respectively, never delivered to multiple sites. Such practices, however, were more common among middlemen – with 33% and 44% always collecting from and delivering to multiple sites.

3.3. Network analysis

3.3.1. Network sampling summary

Of the 379 interviewed egos, 368 (97%) traded pigs in their surveyed recall periods, with 79% and 92% of egos receiving and sending pigs, respectively. Consequently, 11 egos (3%) were network isolates. These were smallholders ($n = 8$) and butchers ($n = 3$). The butchers were excluded from the network analysis as they provided no data for scaling up to 6 months. Hence, the egocentric networks of 376 egos and their swine trading with 4705 alters, involving 669,363 pigs in 6 months are presented here.

3.3.2. Pig movement pathways among value chain actors

The results in this section do not differentiate between breeding- and growing-oriented smallholders due to challenges in differentiating (un-interviewed) smallholder alters by specialisation (see Supplementary Information 3 for further details). With the exception of smallholders, transaction pathways among different actor types were commonly non-reciprocated generating some hierarchical structuring of the value chain from producers, to traders and middlemen, and finally to butchers and

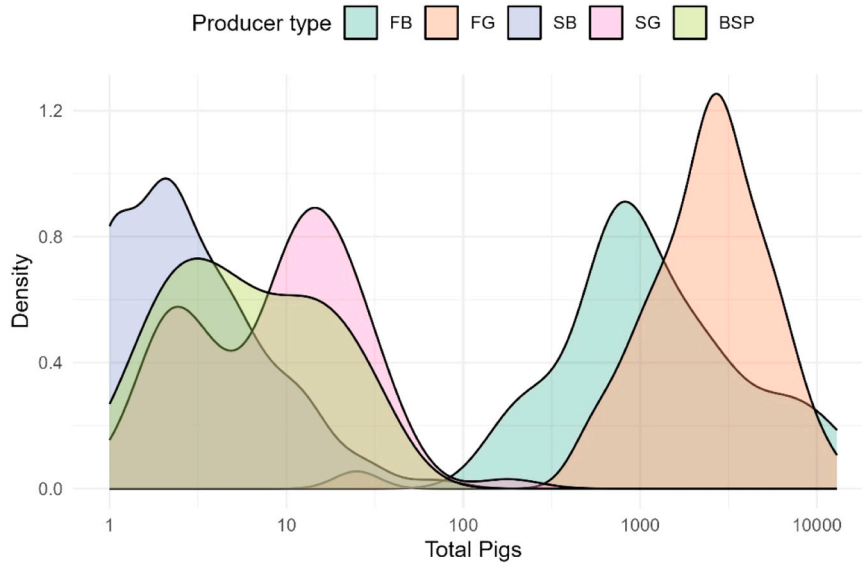


Fig. 2. Probability density function of the number of pigs kept by producers at the time of visit: shown for large breeding farms (FB), large growing farms (FG), breeding-oriented smallholders (SB), growing-oriented smallholders (SG), and boar service providers (BSP).

slaughterhouses (Fig. 3). Further contributing to this hierarchical structuring, large breeding farms, which did not receive pigs from other actor types, supplied pigs to all producer types including smallholders and BSP; though only 1 % of their total outgoing pigs went to these two actor types (Fig. 3a; Table S 7). No transactions were observed between farms associated with different companies. Contrastingly, reciprocated pig movement pathways were commonly observed among smallholders, BSP, and middlemen, with for example, middlemen facilitating the transfer of weaners among smallholders (Fig. 3a). Notably, BSPs made up half of smallholders’ suppliers while 99 % of BSPs suppliers and recipients were smallholders, emphasising the key role of BSP in connecting smallholders (Table S 7). Movement pathways were also observed among actors of the same type as indicated by the self-edges in Fig. 3. Self-edges were commonly reported by smallholders, large breeding farms, and to some extent, among butchers, but were rarely

reported by middlemen and traders (Table S 7).

Butchers, traders, and slaughterhouses were exclusively involved in terminal movements which did not include any transfers of pigs towards producers (Fig. 3b). Some bi-directional flow of pigs was observed between slaughterhouses and traders, representing the collection of pigs in slaughterhouses (n = 2) by traders prior to the transfer of pigs to other slaughterhouses or killing points (i.e. unofficial slaughter locations processing a small number of pigs). Most pigs supplied to slaughterhouses were directly from traders (86 %), butchers (14 %), and smallholders (<1 %), with the pigs from butchers and traders originating from six different companies. Killing points were not directly surveyed. However, two smallholders and four middlemen reported supplying pigs to killing points, and 14 smallholders stated that pigs they sold to butchers (n = 13) and middlemen (n = 1) ultimately ended up at killing points.

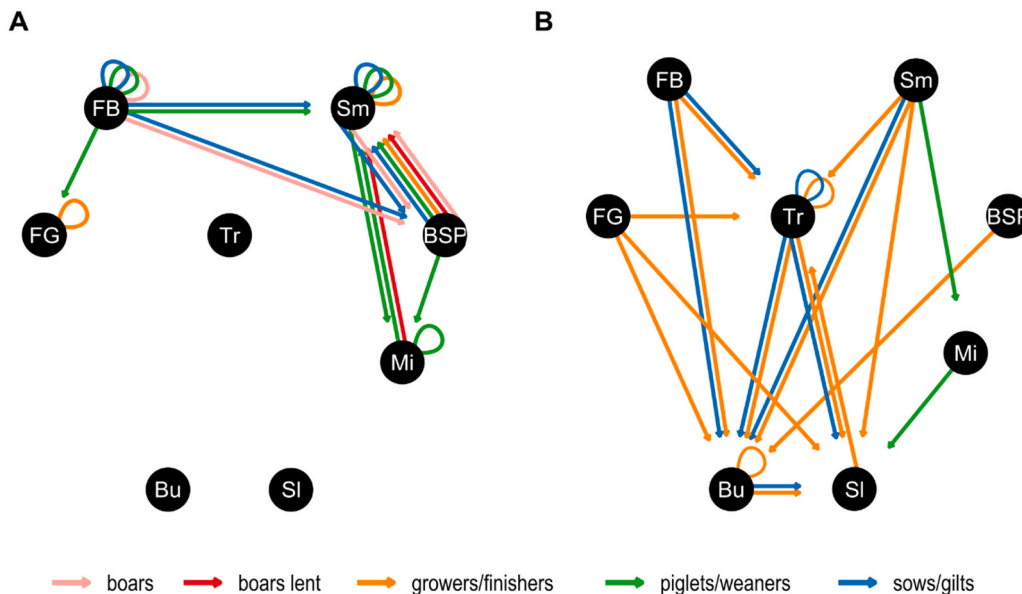


Fig. 3. Pig movement pathways among actor types: Panels show non-terminal (A) and terminal (B) movements. Pig types are shown by coloured arrows. Nodes are the actor types generated via FAMD and HCA: large breeding farms (FB), large growing farms (FG), smallholders (Sm; includes both breeding-oriented and growing-oriented as it was not possible to differentiate smallholder alters by specialisation), boar service providers (BSP), middlemen (Mi), traders (Tr), butchers (Bu) and slaughterhouses (SI).

3.3.3. Distributions of degree, transactions, and strength

Based on their network degree and numbers of transactions, actor types were considered ‘sinks’ when they had many inward connections but no or few outward connections, or ‘brokers’ when they had many inward and many outward connections with producers, indicating that they played a role in connecting pig populations. Breeding- and growing-oriented smallholders were weakly connected to the swine movement network having ≤ 2.1 suppliers (in-degree) and recipients (out-degree) on average (Fig. 4a). Contrastingly, BSP – who had the highest number of alters of any node type – were brokers, having approximately 160 suppliers and recipients on average. Middlemen were also brokers, but had considerably fewer alters than BSP, with 20 suppliers and 14 recipients on average.

Large farms were rarely able to report each individual alter during transactions with company-affiliated farms meaning their network degree was unreliable. Therefore, we interpreted large farm connectivity based on the number of transactions they made and the number of pigs they traded. Based on these metrics, large breeding farms were also brokers, having relatively high numbers of inward and outward transactions compared to most other producers and trading large numbers of pigs (464 pigs received and 5546 pigs sent on average over 6 months) (Fig. 4b-c). Large growing farms, contrastingly, made few transactions which occurred on a 6-monthly basis (i.e. 2 fattening cycles per year; Table S 8) reflecting their all-in-all-out production practices.

Most butchers (96 %; n = 49) and slaughterhouses (81 %; n = 13) were sinks, having no outward pig movements (Fig. 4a-c). Traders had large numbers of inward and outward transactions but exclusively

supplied pigs to sinks (Fig. 4a-c; Fig. 3b).

With the exception of smallholders, actors tended to make repeat transactions with the same trade partners. For example, 48 % of breeding-oriented smallholders’ recipients, and 64 % of growing-oriented smallholders’ suppliers were alters that they had never traded with before (Table S 8).

3.4. Spatio-temporal characteristics of pig trading

3.4.1. Spatial movements

Locations were recorded for alters at province level (79 % of alters), district level (76 %), and commune level (68 %). Egos mostly traded with alters in the same province (84 % of dyads for which alter location was known), district (74 %), and often, commune (50 %). However, distributions of distances connecting egos and alters were often right-skewed, especially for non-terminal movements (Fig. 5).

Large farms rarely knew the locations of their alters (16 %), but reported the longest domestic transportation distances on average, with large breeding farms sending pigs a median 46 km (maximum 126 km) and large growing farms correspondingly sourcing pigs from a median 41 km (maximum 138 km) (Fig. 5). Contrastingly, smallholders mostly traded pigs locally (median <5 km) but sometimes sourced and sent non-terminal pigs at large distances. For example, growing-oriented smallholders sourced weaners from suppliers up to 114 km away.

Most BSP lent boars to customers locally, but sometimes had customers in multiple districts (26 %; n = 5) and frequently, communes (84 %; n = 16) within a two-week period. Compared with smallholders,

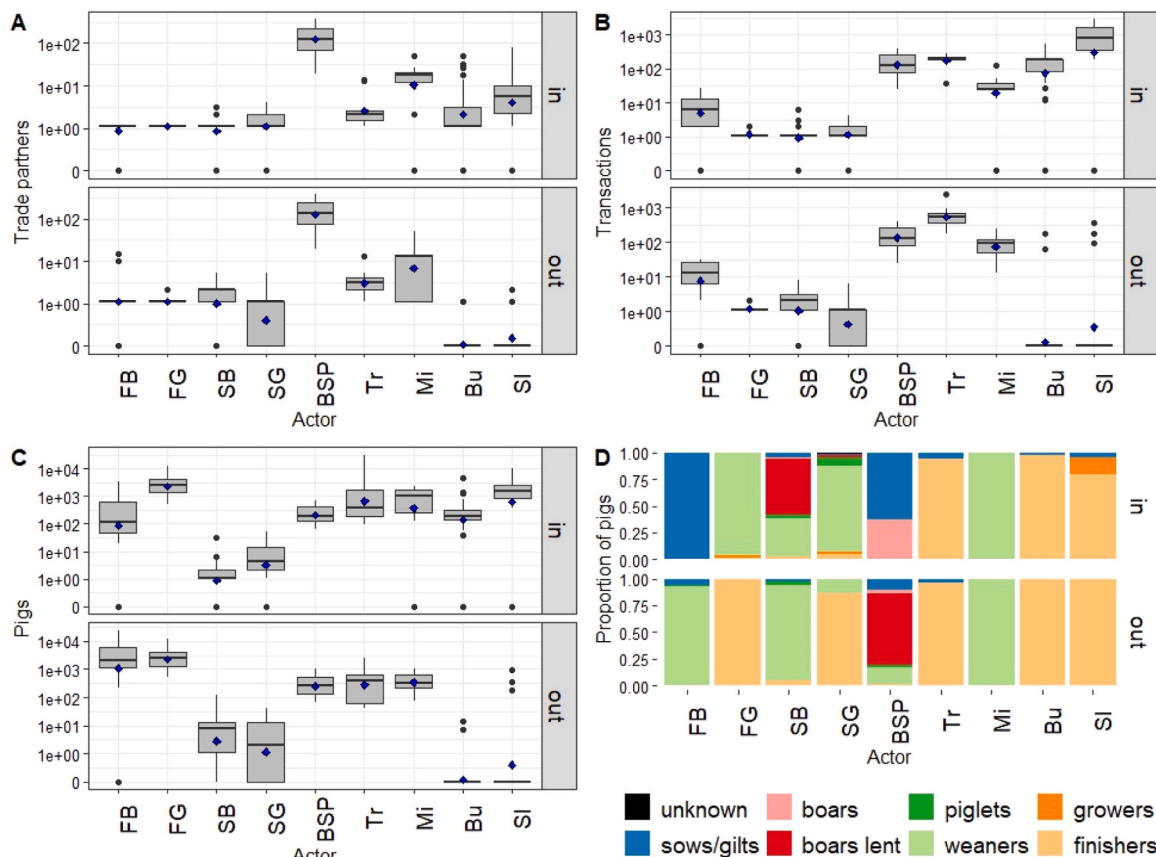


Fig. 4. Egocentric network statistics by actor type: Panels show distributions of degree (A; N.B. FB and FG values are unreliable as they were rarely able to report each individual alter during transactions with company-affiliated farms), the number of transactions made (B), and strength (C; i.e. pig weighted degree) scaled to 6 months; and according to pig categories purchased and sold by actors (D; N.B. FB purchased 4 boars [0.05 % of the pigs they received] which is not easily seen in this plot). Actor types are large breeding farms (FB), large growing farms (FG), breeding-oriented smallholders (SB), growing-oriented smallholders (SG), boar service providers (BSP), traders (Tr), middlemen (Mi), butchers (Bu) and slaughterhouses (SI). Mean values are shown as blue diamonds; outliers, shown as black points, are values beyond 1.5 times the interquartile range. A modified logarithmic scale is used in plots A-C whereby zero values are not log transformed.

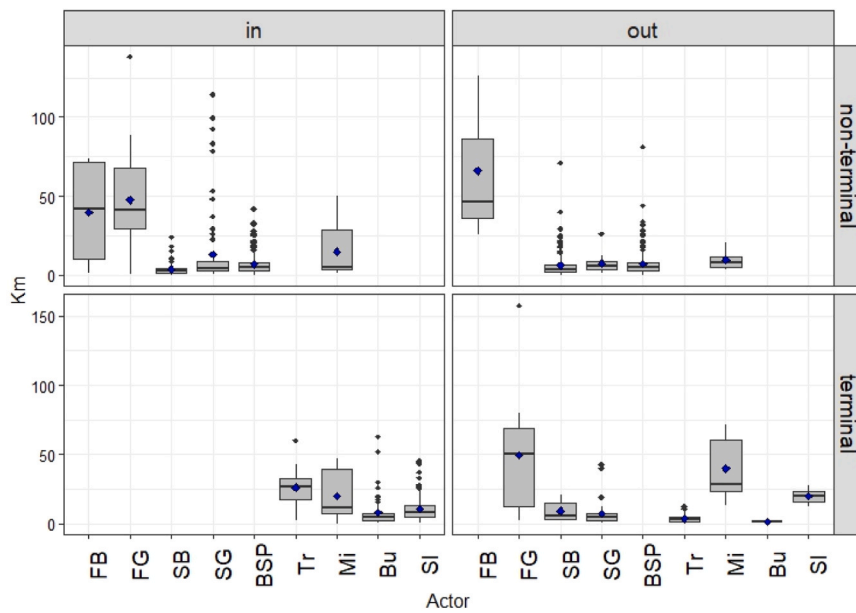


Fig. 5. Geographical Euclidean distances between egos and their alters: Plots are stratified by pigs that egos received (in) and sent (out), and according to whether movements were terminal (i.e. movements for slaughter) or non-terminal. Mean values are shown as blue diamonds; outliers, shown as black points, are values beyond 1.5 times the interquartile range. Actor types are large breeding farms (FB), large growing farms (FG), breeding-oriented smallholders (SB), growing-oriented smallholders (SG), boar service providers (BSP), traders (Tr), middlemen (Mi), butchers (Bu) and slaughterhouses (Sl).

middlemen tended to source pigs from more distant alters on average. They would then either supply these weaners to their local smallholders (non-terminal movements) or to more distant slaughter locations (terminal movements) (Fig. 5).

Cross-border movements of terminal pigs were reported by slaughterhouses in Phnom Penh (n = 3) and Kandal (n = 3). These actors received pigs from Thailand via 26 pig exchanger alters, 23 (88 %) of whom were daily contacts. No imports were observed from other countries.

3.4.2. Temporal variation in pig trading activity

All slaughterhouses reported temporal variation in the number of pigs received (100 %; n = 16). Most slaughterhouses reported peaks in April and October, and some in late January (Figure S 4a) corresponding respectively with Khmer New Year, Pchum Ben, and Lunar New Year. Butchers and traders experienced similar peaks in their pig trading activities (Figure S 4c). Middlemen reported peak trading periods between January and April (Figure S 4e). Most BSP (83 %) reported no temporal variation in their business.

3.5. Producers' pig health status and risk-factor analysis

Overall, 102 (35 %) producers reported pig morbidity but few (n = 9; 9 %) were able to report the names of suspected diseases affecting their pigs. Two farms reported salmonella as the causative agent, while growing-oriented smallholders reported salmonella (n = 1 smallholder), PRRS (n = 1), Classical swine fever (n = 1), and FMD (n = 1). BSP were the only producer types to report ASF as the causative agent (n = 3; 16 %).

Based on the number of pig mortalities reported by producers, we calculated that 19 (27 %) farms and 22 (12 %) smallholders had a mortality risk $\geq 5\%$ of their current herd size in the past 6 months (Table 2). Producer type was significantly associated with odds of high ($\geq 5\%$) pig mortalities based on univariable logistic regression. Compared to breeding-oriented smallholders, BSP had 8.1 times greater odds (95 % CI: 2.4–27.8) of self-reported pig mortalities affecting 5 % of their current herd size in the past 6 months (Table 2). Large breeding

Table 2

Univariable logistic regression of the odds of self-reporting a mortality risk $\geq 5\%$ of the current herd size in the previous 6 months (based on the herd size at interview). Separate analyses for smallholders and farms are shown.

Variables	Total actors n	Mortality risk $\geq 5\%$ n (%)	Univariable logistic regression		
			Odds ratio	95 % CIs	p-value
Smallholder analysis					
Smallholder type			reference		
Breeding-oriented	104	7 (6.7)			
Growing-oriented	77	8 (10.4)	1.6	(0.55–4.78)	0.38
Boar service provider	19	7 (36.8)	8.1	(2.4–27.8)	< 0.001
Large farm analysis					
Large farm type			reference		
Growing	68	9 (13.2)			
Breeding	21	10 (47.6)	6.0	(2.0–18.6)	0.002

farms meanwhile had 6.0 times (95 % CI: 2.0–18.6) greater odds of the outcome compared to growing farms.

4. Discussion

This study defined a data-driven typology of swine value chain actors in Cambodia and characterised their egocentric trade networks. Data collection coincided with COVID-19 and ASF epidemics, possibly influencing trade patterns (Camerons et al., 2022; Qiu et al., 2020) and necessitating temporally scattered surveys over a two-year period. While potentially limiting the generalisability of the collected data to other time periods or regions, this study nonetheless provides valuable insight into live pig trade in a region where such data are limited. Moreover, in the context of ongoing disease threats such as ASF, these findings have relevance for developing resource-efficient and context-adapted disease monitoring and control strategies in Cambodia. Here, we discuss (a)

network-based disease introduction and dissemination risks among actor types, (b) their relevance for risk-stratification, (c) ASF disease management opportunities, and (d) the value of egocentric sampling for livestock network characterisation.

Egocentric network analysis revealed actor types that were network brokers and sinks. BSP, middlemen, and large breeding farms were brokers, underscoring their role in connecting pig populations and positioning them at an elevated risk of disease introduction and onward dissemination. BSP and breeding farms were indeed more likely to report high pig mortalities based on univariable logistic regression. However, this could also be explained by factors other than infectious disease. For example, in large farms, this association may instead reflect expected losses among reproductive sows and pre-weaning piglets (present in breeding farms and not growing farms).

Notably, BSP had the highest average in- and out-degree of any actor type, reflecting the common practice among smallholders, of hiring boars for breeding – practices observed in other Cambodian provinces and across SEA (Baudon et al., 2017a; Chea et al., 2020; FAO, 2011; Huynh et al., 2006; Leslie et al., 2015). Middlemen, who transferred weaners between smallholders, also had high in- and out-degree, though notably lower than BSP. Middlemen and BSP therefore play a central role in linking otherwise poorly connected smallholders, presenting opportunities for targeted disease control, as discussed later in the context of ASF.

Large breeding farms had high in- and out- transaction counts from frequent weaner sales and restocking of sows and gilts (i.e. unmated females). The degree of large farms could not be reliably quantified as they rarely knew the number of supplying or receiving farm(s) during transactions with company-affiliated farms, instead only naming the company. Nevertheless, movement pathways from large breeding farms to all producer types underscores their potential for pathogen dissemination through the value chain. Notably, this included smallholders and BSP who occasionally received weaners and breeding stock (sows and boars) from large breeding farms – a practice also observed in other Cambodian provinces (Chea et al., 2020). While this enables sourcing from higher biosecurity suppliers, it also bridges contrasting production types. Our previous work demonstrated higher virological and serological prevalence of IAV among pigs from commercial compared to smallholder farms in our study area (Hidano et al., 2024), consistent with broader prevalence patterns among farmed pigs (Baudon et al., 2017b). Such movements may therefore represent an interface for pathogen exchange from large farms to low-biosecurity smallholders, where conditions are fertile for inter-species (e.g. pig-poultry) transmission.

Slaughterhouses and butchers were network sinks, with butchers then supplying those pigs to slaughterhouses. As slaughterhouses received pigs from both smallholders and multiple companies, they represent efficient targets for disease monitoring across a diversity of companies and farming types. However, since most slaughterhouse supply was via traders and butchers, identifying the production origins of pigs and/or their point of exposure would likely require interviews with these suppliers during pig deliveries. The feasibility of this strategy has been recently demonstrated through IAV surveillance conducted in the slaughterhouses studied here (Zeller et al., 2023). Slaughterhouse surveillance can consequently serve as a practical and cost-effective approach for assessing pathogen diversity while limiting the need for farm visits which may present logistical challenges and biosecurity concerns.

Actor typologies revealed clear heterogeneity in herd management, trading practices, and biosecurity measures among actors, which combined with their varying network positions, suggests a high relevance for actor-based disease risk-stratification. Some producer types aligned with official classifications, facilitating their identification through official registries. For example, our findings were consistent with official definitions of producers with 100 or more pigs as farms, and others as smallholders (MAFF, 2018), while farm specialisations (FB and FG)

matched records held by government veterinarians. In contrast, registries were absent for BSP and unlicensed pig exchangers, and licensed pig exchangers (Tr, Mi, Bu) could not be distinguished from official records alone. While this may leave such actors challenging to identify, targeted interventions at these actors could instead be achieved through contact nominations (e.g. respondent-driven sampling) as demonstrated here.

Various trade-, pig management-, and biosecurity-practices were observed which could epidemiologically connect producers via contaminated vehicles, equipment, or personnel. All pig exchanger types (Tr, Mi, Bu) entered holding areas to load and unload pigs, with over a third of each type always doing so. Additionally, pig exchangers sometimes visited multiple sites per trip – a practice especially common among middlemen, with around a third to half always doing so when collecting or delivering pigs. These practices have been shown to be prevalent among swine traders in other provinces (Chea et al., 2020) and livestock traders across Cambodia (ACIAR, 2012; Poolkhet et al., 2016). Such practices therefore represent a high risk for swine pathogens transmitted through fomites, including ASF virus.

In the context of the ongoing ASF epidemic in SEA, the egocentric swine trade networks, actor typologies, and disease risk hotspots described in this study provide information considered critical for long-term control in the region (Kalpravidh and Holley, 2019). BSP and middlemen contributed to a large proportion of live pig movements among smallholders and exhibited practices which carry a high risk of fomite transmission. BSP also reported ASF outbreaks in their herds, underscoring the transmission risk through these actors. While serving important production roles, BSP and middlemen may therefore present a challenge to control. Targeting these brokers with knowledge-based interventions like biocontainment and biosecurity training could serve as a strategic and resource-efficient approach to limit ASF transmission among smallholders. The promotion of artificial insemination (AI) could further reduce transmission risks by reducing the number of boar movements. While requiring investment in training, equipment, and access to pathogen-free germplasm (FAO, WOA, World Bank, 2010; Kadirvel et al., 2013), AI was already adopted by some smallholders in this study. The feasibility and upscaling of AI has been demonstrated by smallholders in other settings, where it has been associated with improved productivity and profitability (Am-in et al., 2010; Sharma et al., 2020; Singh et al., 2022) while serving as an income stream for BSP (Pena et al., 2023). Further research is needed to fully characterise the ASF-risk interface between smallholders and commercial farms, particularly the infection risk to large farms during their supply of pigs to smallholders.

This study had limitations beyond its constrained temporal and geographical representativeness. We adopted different recall periods for producers, exchangers, and slaughterhouses to reduce respondent burden and eliminate biases from alter truncation. Nevertheless, comparisons of degree, transactions, and strength required re-scaling these measures to equal recall periods which may have introduced error. Since surveys were conducted at varying times of year, seasonal fluctuations in trading activity may have affected reported values and introduced biases in rescaled measures of network connectivity. Furthermore, the use of link-trace sampling for some BSP and middlemen may have overestimated their connectivity as high-degree nodes are more likely to be sampled (Robins, 2015). However, this affected only a small fraction of egos. Despite measures taken to validate information provided during interviews, the reliance on participant recall, and potential sensitivities around production and trading practices may have introduced bias. Finally, limited spatial coverage may have excluded some farm types and trade structures present in other provinces.

Nevertheless, this study demonstrates the utility of egocentric sampling for characterising livestock trade networks. By quantifying node-level metrics like degree, strength, and transaction frequency, egocentric approaches can provide valuable insights into disease transmission dynamics (Kiss et al., 2006; Lebl et al., 2016; Volkova et al., 2010).

While egocentric approaches do not directly quantify global network statistics like clustering and component sizes, methodological developments in statistical network simulation modelling present opportunities to infer whole network properties from egocentric networks (e.g. Krivitsky and Morris, 2017; Robins, 2015; Smith, 2012).

In conclusion, this study identifies network brokers and sinks which are relevant targets for disease control and surveillance in Cambodia's swine sector. Targeted interventions at brokers, especially BSP and middlemen, including biosecurity training, could reduce the likelihood of onward transmission from these nodes. The promotion of artificial insemination, with appropriate veterinary, logistical, and infrastructure support could further reduce transmission risks associated with boar movements while supporting smallholder productivity. Slaughterhouse surveillance can serve as a cost-effective means of monitoring pathogen diversity across production systems.

Ethics statement

Ethical approval was received by the Cambodian National Ethics Committee for Health Research (#325), LSHTM Institutional Review Board (#16635 and 17973) and Animal Welfare and Ethical Review Board (#2019-12), the US Army Medical Research and Development Command's Human Research Protections Office (#A-21055) and Animal Care and Use Review Office (#2019-12). Written consent was obtained from all participants. An independent witness observed the consent process for illiterate individuals.

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CRediT authorship contribution statement

Hannah Holt: Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition. **Arata Hidano:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Ty Chhay:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Phalla Miech:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **James W. Rudge:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Guillaume Fournié:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Gavin J.D. Smith:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **William T.M. Leung:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yvonne C. F. Su:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Monidarin Chou:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Sothyra Tum:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Son Pov:** Writing – review & editing, Resources, Investigation, Data curation. **Sokchea Huy:** Writing – review & editing, Resources, Methodology, Investigation, Data curation. **Sina Vor:** Writing – review & editing, Resources, Methodology, Investigation, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.prevetmed.2025.106724](https://doi.org/10.1016/j.prevetmed.2025.106724).

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