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13 **Social network analysis of the movement of poultry to and from live bird markets in Bali**
14 **and Lombok, Indonesia**

15

16 Abbreviated title: **Analyses of poultry movement networks in Indonesia**

17

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40 **Summary**

41 Highly pathogenic avian influenza H5N1 has resulted in large losses to the Indonesian poultry
42 sector. Evidence suggests that live bird markets (LBMs) play an important role in the
43 epidemiology of the disease. Knowledge of the frequency and type of contact between the
44 various poultry market players should allow animal health authorities to develop a better
45 understanding of factors influencing virus transmission between Indonesian villages. A
46 questionnaire-based cross-sectional survey was conducted in 17 LBMs on the neighbouring
47 Indonesian islands of Bali and Lombok to investigate the movement patterns of poultry to and
48 from markets. Using social network analyses, a network of contacts was created for each island
49 from a total of 413 live poultry traders and 134 customers. Individual nodes with high degree
50 and/or betweenness were identified in each network. The Lombok network was more dense and
51 connected than the Bali network indicating that disease transmission would be more efficient in
52 the Lombok network. Our findings indicate that whilst live poultry are typically transported over
53 relatively short distances of approximately 10 km, it is not uncommon for traders and customers
54 to travel in excess of 100 km to buy or sell poultry, which may facilitate the spread of disease
55 over a large geographical area. This study highlights the different roles markets play in poultry
56 movement networks and their potential for disease dissemination. The identification of highly
57 influential market nodes allows authorities to target HPAI surveillance activities to locations
58 where disease is more likely to be present, which is crucial in low-resource settings.

59

60 **Keywords:** highly pathogenic avian influenza, H5N1, Indonesia, live bird markets, social
61 network analysis.

62
63

64 **Introduction**

65 The emergence of highly pathogenic avian influenza (HPAI) subtype H5N1 in Indonesia in 2003
66 resulted in large losses to the poultry sector and the highest number of H5N1-related human
67 deaths to date in a single country (Perez et al., 2002). Despite an overall decline in the incidence
68 of HPAI H5N1 in poultry and humans in recent years, Indonesia experienced a sharp increase in
69 the number of reported HPAI H5N1 outbreaks in poultry in 2016. During the first four months
70 of 2016 alone, 148 cases were reported in poultry compared to 123 cases in 2015 (FAO, 2016).
71 The rise in newly emergent AIVs in the Asian region such as H5N6, H5N8 and H7N9 pose an
72 additional threat to both poultry and human health (Hall et al., 2015; Joob and Viroj, 2015; FAO,
73 2014; Wiwanitkit, 2013).

74
75 Indonesians, in common with most nationalities in South East Asia prefer to purchase live
76 poultry, which are largely traded through live bird markets (LBMs), because they are cheaper
77 and the customer can be assured that poultry meat is fresh and free of disease (Patrick et al.,
78 2014). The mixing of different avian species from various sources means that LBMs provide an
79 ideal environment for virus exchange (Morris et al., 2005). Available evidence suggests that
80 LBMs play a crucial role in the epidemiology of avian influenza viruses (AIVs) in countries
81 where live birds are sold to customers (Fournié et al., 2012; Indriani et al., 2010; Ge et al., 2009).
82 A recent study modelled the risk of HPAI H5N1 transmission through poultry movements in
83 Bali concluded that there is a high risk of a LBM being infected despite a low level of disease at
84 the village level (Roche et al., 2014). The limited resources available in Indonesia for market
85 infrastructure and management often results in loosely controlled and regulated markets
86 (Suryadarma et al., 2007) with limited or no biosecurity. This may facilitate the circulation and
87 dissemination of avian influenza viruses through the movement of poultry, poultry products and
88 fomites.

89
90 Knowledge of the type and magnitude of contacts between the various poultry market players
91 allows animal health authorities to develop a better understanding of factors influencing virus
92 transmission. To-date, information is limited on the types and frequencies of contacts that exist
93 between live bird markets and poultry traders in Bali and Lombok, and how these contacts might

94 influence or act as pathogen transmission routes. This information could be useful in identifying
95 villages and markets that are at a greater risk of receiving and dispersing infectious material
96 throughout a network.

97
98 In order to establish a network of contacts, information on the movement of poultry between
99 markets and villages is required. This can be achieved by carrying out a survey to document the
100 source and destination village of birds traded in a market, and then analysing the accumulated
101 data using social network analyses (SNA). Social network analyses are concerned with
102 'relationships' that exist between pairs of individuals in a given study population as opposed to
103 characteristics of the individuals themselves (Borgatti et al., 2009). This perspective recognises
104 that the way in which individuals are connected in a population are important determinants of
105 infection spread (Luke and Harris, 2007).

106
107 Although SNA was initially used in the social sciences (Borgatti et al., 2009), it has gained
108 popularity in veterinary epidemiological research. In recent years, network analysis has been
109 used to investigate associations between poultry trade networks and trader practices in Cambodia
110 (Van Kerkhove et al., 2009) poultry trade networks and HPAI H5N1 outbreaks in Vietnam
111 (Soares Magalhães et al., 2010) and China (Martin et al., 2011) and in the identification of high
112 risk players in the backyard poultry industry in Thailand (Poolkhet et al., 2013). Social network
113 analysis is also a useful tool to identify markets that pose a greater threat in terms of disease
114 transmission potential as demonstrated by Fournié et al. (Fournie et al., 2013).

115
116 With this background, the aim of this study was to use social network analysis to investigate the
117 movement patterns of poultry to and from live bird markets in Bali and Lombok, and to describe
118 the topology and network of contacts between villages. This will allow for a better understanding
119 of the potential for transmission of disease arising from movement of birds between villages and
120 markets. Information gathered from studies of this type can be used to identify highly connected
121 nodes (i.e. villages and markets) within each network. Based on the biologically plausible
122 assumption that highly connected nodes are more likely to either receive or distribute infection,
123 these locations can then be preferentially targeted for surveillance or enhanced biosecurity
124 measures (Martin, 2006; Christley, 2005).

125

126 **Materials and methods**

127 A detailed description of the methods used in this study are provided by Kurscheid et al. (2015).
128 The following sections contain a brief overview of the study methods and additional details not
129 published elsewhere.

130

131 **Study location and respondents**

132 A cross-sectional study of live poultry traders (vendors and collectors) and customers (those
133 purchasing poultry) was carried out between 2008 and 2009 at nine LBMs in Bali (representing
134 approximately 8% of the estimated 109 LBMs) and eight in Lombok (22% of the 36 known
135 LBMs). Markets were selected based on the following criteria: size of the market; approximate
136 volume of poultry traded per day; medium to high flow of road traffic (expected to have a larger
137 customer base) surrounding the market; operating frequency; poultry farm density in the
138 surrounding area; and whether there had been any locally confirmed reports (i.e. confirmed by
139 the Regional Office of Livestock and Animal Health) of HPAI H5N1 outbreaks in poultry in the
140 previous 12 months.

141
142 Traders were defined as either a 'vendor' (i.e. retailers) or a 'collector' (poultry wholesalers)
143 depending on their role in the market. Vendors primarily sold live poultry directly to customers
144 at the market, whereas collectors collected live poultry from all sectors of the poultry industry
145 and transported them to the markets either on the same day or a few days later and selling to both
146 LBM vendors and customers (Kurscheid et al. 2015). Customers were defined as individuals
147 purchasing live poultry (i.e. not slaughtered or dressed birds) from vendors or collectors on the
148 day of interview for a variety of purposes (e.g. special cultural or religious events, consumption
149 at home or restaurant and restocking). Study participants were comprised of individuals that
150 were engaged in one of the three aforementioned roles at the market on the day of interview and
151 selected using convenience sampling. The numbers of respondents interviewed at each of the
152 surveyed markets, along with estimates of each group of respondents frequenting the markets on
153 a daily basis, are shown in Tables S3 and S4 of the Supplementary Information. In the remainder
154 of this paper the term 'respondent' is used to refer to individuals interviewed for this study.

155

156 **Data collection**

157 A semi-structured questionnaire was developed for each of the three categories of respondents in
158 English and translated into Bahasa Indonesia. Questionnaires were administered by face-to-face
159 interviews. Poultry traders were asked to provide details of: (1) the origin of birds being sold,
160 including the type of source (e.g. backyard farm, commercial farm, market or trader); (2) the

161 type and number of birds sold on the previous trading day brought to the market for sale; and (3)
162 other markets where birds were sold. Customers were asked to provide details of: (1) the
163 destination of birds purchased on the day of interview; (2) other markets where birds were
164 purchased; and (3) the number of birds purchased on the day of interview.

165

166 **Data management and analysis**

167 Data from the interviews were entered into a relational database (Microsoft Office Access 2003).
168 The database contained three groups of tables: (1) poultry traders, (2) poultry customers, and (3)
169 village locations. Contacts were defined by the direction of poultry movement, either inbound or
170 outbound, and the village of origin or destination. The interview responses from the database
171 were exported to a social network analysis package (UCINET v6.137 Analytic Technologies
172 Inc., Harvard, Massachusetts, USA).

173

174 The names of each of the villages cited by the respondents were cross-matched with digital maps
175 of village and town locations in Bali and Lombok (Anonymous 2014) using the Geographic
176 Information System Quantum GIS (Quantum GIS Development Team 2016) and Google Earth
177 (Google Earth v5.1, Google Inc., Mountain View, USA) to obtain the longitude and latitude
178 coordinates of the village centroid. In the event that coordinates for a village provided by the
179 respondent were not available, those of the nearest village were used. Given that villages of the
180 same name are found in multiple districts throughout each island, the coordinates of duplicate
181 villages closest to the market where interviews took place were used based on interviewer
182 feedback, on the assumption that respondents lived close to the markets where the interviews
183 were taking place.

184

185 Descriptive analyses of the data consisted of summary statistics of surveyed participants
186 stratified by direction of movement (to or from a market) and location (source or destination of
187 poultry). Straight-line (Euclidean) distances travelled by respondents transporting live birds to
188 and from markets (in kilometres) were calculated using the latitude and longitude of villages and
189 markets using the fields package in R (Nychka et al., 2015).

190

191 The presence of a recorded movement event between locations (i.e. markets and/or villages), and
192 the type of respondent (trader vs. customer) allowed us to construct a network of contacts. Using
193 this approach, markets and villages formed the nodes (vertices) of the network and the presence
194 of a stated movement of live poultry from one node to another formed binary ties. Under the

195 assumption that transactions between markets and villages were in a specific direction (i.e. from
196 market to village, or village to market), all networks were treated as directed.

197
198 Contact networks were constructed for movements relating to the sale or purchase of live
199 poultry. Each network was described in terms of: (1) the number of nodes and directed links; (2)
200 the network size, diameter and density; and (3) the number of reachable pairs of nodes and the
201 proportion of pairs that were reachable. The following parameters were calculated for each node
202 of the network and summarised for the entire network, using frequency histograms and
203 descriptive statistics: in- and out-degree, in- and out-degree centralisation, betweenness and
204 geodesic distance. In addition to absolute measures of node centrality (e.g. in-degree, out-degree
205 and betweenness) normalised centrality measures were calculated as the absolute score divided
206 by the maximum score for the given measure, expressed as a proportion. Normalisation allowed
207 node centrality measures for the two networks (Bali, Lombok) to be compared. Network
208 diagrams were constructed for the two networks. Information regarding the key metrics of social
209 network analysis can be found in the review of Dubé et al. (Dubé et al., 2009). Additional metric
210 definitions are provided in the footnotes of Table 1.

211
212 The association between normalised in-and out-degree indices and normalised total degree and
213 normalised betweenness was quantified using Spearman's rho.

214

215 **Ethics statement**

216 The study protocol was reviewed and approved by the Murdoch University Human Research
217 Ethics Committee, Perth, Western Australia (Permit number 2008/162). Further details are
218 provided by Kurscheid et al. (2015).

219

220 **Results**

221 **Respondents**

222 A total of 413 (Bali $n = 195$, Lombok $n = 218$) traders and 134 (Bali $n = 52$, Lombok $n = 82$)
223 customers participated in this study. Of these, source and destination information was elicited
224 from 95% of respondents from Bali ($n = 184$ traders and $n = 50$ customers) and 90% from
225 Lombok ($n = 196$ traders and $n = 74$ customers). The remaining 43 respondents ($n = 13$ and 30
226 from Bali and Lombok, respectively) either did not provide information about where birds were
227 transported to and from, or the GPS locations of village names provided were not available. The
228 survey refusal rate was zero.

229

230 **Network size**

231 The two networks created for the movements of live poultry to and from live bird markets were
232 comprised of 9 markets and 130 villages in Bali (Fig. 1) and 8 markets and 134 villages in
233 Lombok (Fig. 2). Although the number of nodes (i.e. network size) was similar for the two
234 networks (139 for Bali and 142 for Lombok), Lombok recorded more than twice the number of
235 links compared to the Bali network (880 vs 373, Table 1).

236

237 Fig. 1 Bali network projected onto geographical map of Bali. Villages and surveyed markets
238 represented by blue and red nodes, respectively.

239

240 Fig. 2 Lombok network projected onto map of Lombok. Villages and surveyed markets
241 represented by blue and red nodes, respectively.

242

243 **Centrality**

244 *Degree*

245 Inspection of plots of the cumulative distribution of degree among nodes showed highly skewed
246 degree distributions for both networks with power law function parameters of 2.04 and 2.14 for
247 Bali and Lombok, respectively (see Figures S3 and S4 in the Supplementary Information). The
248 number of incoming movements varied more widely than outgoing, indicated by the higher in-
249 vs. out-degree centralisation values for both networks (Table 1). However, nodes with a null in-
250 degree (i.e. villages that did not receive poultry from any other village) outnumbered those with
251 a null out-degree (i.e. those villages that did not distribute poultry to other markets or villages)
252 for both the Bali ($n = 82$ vs. 26) and Lombok networks ($n = 82$ vs. 25). Hence, the majority of
253 nodes within each network had at least one out-going and no incoming poultry movements and
254 only a few had a large number of incoming movements compared with outgoing movements.

255

256 The maximum number of incoming movements recorded for a single node was 2.4 times greater
257 for Lombok than for Bali ($n = 125$ vs. 52). The Lombok network also showed greater variation in
258 incoming movements compared to the Bali network, as indicated by the higher normalised
259 values for the mean (0.04 vs. 0.02, respectively) and range of in-degree scores (0 – 0.89 vs. 0 –
260 0.38). Normalised out-degree centralisation values and the range of out-degree scores showed a
261 similar pattern (Table 1). Although the numbers of incoming and outgoing movement events
262 were greater among markets in Lombok, the proportions of movements to and from unique
263 contacts were higher in Bali (Supplementary Information). Another difference between the two

264 networks in terms of degree was that for Lombok, non-surveyed villages had high degree scores
 265 as well as the surveyed markets. In Bali, on the other hand, only the surveyed markets had high
 266 degree scores. The number of movements recorded for non-surveyed nodes in the Bali network
 267 were relatively small in comparison with inbound movements ranging between one and four and
 268 outbound between one and ten.

269
 270 Normalised values for in- and out-degree were plotted against each other for the two networks
 271 (Fig. 3) to determine if villages and markets that had a high number of incoming poultry
 272 movement events also had a high number of outgoing poultry movement events. Plots for each
 273 network indicated that a correlation was present. To evaluate this further in-and out-degree
 274 indices for all nodes were analysed using the Spearman's rho test. The resultant R-values showed
 275 that a statistically significant correlation between normalised in-degree and out-degree was
 276 present for Lombok ($R = 0.31$, $p < 0.001$) but not for Bali ($R = -0.10$, $p = 0.241$). However, a
 277 statistically significant positive correlation was identified between in- and out-degree among the
 278 surveyed market nodes in the Bali network ($R = 0.69$, $p = 0.040$) but not among the surveyed
 279 market nodes in the Lombok network ($R = 0.65$, $P > 0.05$).

280

281 Table 1. Summary statistics for the Bali and Lombok networks

Parameter ^a	Bali network	Lombok network
Network size		
Number of nodes	139	142
Number of directed links	373	880
Size	19182	20022
Diameter	6	8
Measures of centrality		
Mean in-degree (range)	2.68 (0 - 52)	6.20 (0 - 125)
Mean out-degree (range)	2.68 (0 - 33)	6.20 (0 - 61)
Normalised mean in-degree (range)	0.02 (0 - 0.38)	0.04 (0 - 0.89)
Normalised mean out-degree (range)	0.02 (0 - 0.24)	0.04 (0 - 0.43)
In-degree centralisation	0.36	0.84
Out-degree centralisation	0.22	0.39
Mean betweenness (range)	25.46 (0-651)	111.50 (0 - 3259)
Normalised mean betweenness (range)	0.00 (0-0.03)	0.01 (0 - 0.17)
Betweenness centralisation	0.03	0.16
Measures of cohesion		
Density (directed)	0.02	0.04
Mean geodesic distance (mode)	3.79 (4)	2.69 (3)

Number of reachable pairs	2292	8035
Proportion of reachable pairs	10.9%	40.0%
Clustering coefficient ^b	0.16	0.40
Distance-based cohesion (or compactness) ^c	0.04	0.16
Distance-weighted fragmentation ^d	0.96	0.84

282 ^a See Dubé et al. (2009) for definitions of network parameters.

283 ^b Calculated on undirected networks.

284 ^c Compactness is the normalized sum of the reciprocal of all the distances (i.e. based on the lengths of paths). This
 285 has a value of 1 when the network is a clique (everyone is adjacent) and zero when the network is entirely made up
 286 of isolates.

287 ^d Distance-weighted fragmentation is 1 minus compactness and describes the breadth of the network (Borgatti,
 288 2006).

289
 290 Fig. 3 Scatterplot of normalised out-degree as a function of normalised in-degree for the Bali and
 291 Lombok networks.

292
 293 **Betweenness**

294 Although the normalised mean betweenness scores for both networks were similar (0.00 vs. 0.01,
 295 for Bali and Lombok, respectively) both the maximum betweenness value and betweenness
 296 centralisation indices for the Lombok network were five times greater than for the Bali network
 297 (Table 1). Scatterplots of normalised betweenness as a function of total degree (Fig. 4) showed a
 298 positive correlation between the two measures for both networks. This was further demonstrated
 299 using the Spearman's Rho test, producing R-values of 0.54 ($p < 0.001$) and 0.73 ($p < 0.001$) for
 300 Bali and Lombok, respectively. A statistically significant association between degree and
 301 betweenness for markets was identified in the Lombok network ($R = 0.87$, $p = 0.004$) but not in
 302 the Bali network ($R = 0.48$, $p > 0.05$).

303
 304 Fig. 4 Scatterplot of normalised betweenness as a function of normalised total degree for the Bali
 305 and Lombok networks.

306
 307 **Network cohesion and topological features**

308 The density (i.e. the proportion of potential contacts in a network that were actually present) for
 309 both networks was low (2% for Bali and 4% for Lombok) which is not surprising because the
 310 data were collected from a subset of LBMs in each island. Although the cohesion (i.e.
 311 compactness) score for the Lombok network was four times higher than the Bali network (0.04
 312 vs. 0.16), both values were relatively low. Both networks had similar, relatively high

313 fragmentation scores (0.84 and 0.96 for Lombok and Bali, respectively). The total number of
314 reachable pairs of nodes within the Lombok network was 8035 representing 40% of all possible
315 pairs, which was 3.5 times as many as in the Bali network (2292, 11%). Furthermore, the
316 average number of nodes that could reach other nodes was 56.8 in in the Lombok network
317 compared with 15.4 in the Bali network. The proportion of nodes that had zero reachability (i.e.
318 had no outgoing poultry movements and therefore could not reach any other node) was similar
319 for Bali (19%, $n = 26$) and Lombok (18%, $n = 25$).

320
321 Geodesic distances between pairs of reachable nodes varied more widely in the Bali network
322 (Fig. 5) resulting in a larger mean geodesic distance of 3.79 compared to 2.69 for the Lombok
323 network. Mode values for geodesic distance indicated that most nodes within the Lombok
324 network could be reached within three ‘jumps’ compared to four in the Bali network. The
325 clustering coefficient for the Bali network was relatively small compared with the Lombok
326 network (0.16 vs. 0.40). A random (directed) network of similar size to the Bali network
327 produced a mean geodesic distance of 4.8 and a clustering coefficient of 0.02. The mean
328 geodesic distance and clustering coefficient for a random (directed) network of similar size to the
329 Lombok network was 3.0 and 0.04, respectively.

330

331 Fig. 5 Frequency histogram of geodesic distances for the Bali and Lombok networks.

332

333 **Movement distances**

334 Respondents in Bali transported poultry over slightly shorter distances (median = 5.3 km, IQR:
335 2.3-12 km) than Lombok (median 8.6 km, IQR: 4.6-16 km). However, the range of distances was
336 similar for the two islands (0-111 km and 0–122 km, respectively), with the greatest distance in
337 Lombok occurring between two villages as opposed to between a market and village in Bali.
338 Comparison of distances travelled by respondent categories showed little differences between
339 vendors (median = 7.3 km, IQR: 4.2-15 km) and collectors (median = 9.8 km, IQR: 5.5-16 km).
340 Traders, in general, transported birds over greater distances compared to customers (median =
341 4.4 km, IQR: 1.8-10 km). The average movement distances of each respondent type differed
342 significantly in Lombok ($F_{2,877} = 7.90$, $p < .001$) but not in Bali ($F_{2,370} = 1.08$, $p > 0.05$). *Post-hoc*
343 analysis of average distances travelled by respondents in Lombok identified significant
344 differences between vendors and customers ($p = 0.003$) and collectors and customers ($p < 0.001$)
345 but not between vendors and collectors ($p > 0.05$).

346

347 Village-to-market (median 7.7 km, IQR: 3.2-13 km) and market-to-village movement distances
348 (median 7.7 km, IQR: 4.6-14 km) in Lombok were almost identical however the maximum
349 distance travelled in Lombok was greater for market-to-village movements (105 km vs. 66 km).
350 In contrast, maximum distances travelled in either direction in Bali were the same (112 km),
351 whilst village-to-market distances (median = 5.3 km, IQR: 2.6-12 km) were slightly greater than
352 market-to-village movement distances (median = 3.5 km, IQR: 0.0-3.9 km). Box and whisker
353 plots of market-to-village and village-to-market movement distances for each of the surveyed
354 markets and for the three different respondent types are provided in the Supplementary
355 Information (Figures S5 to S12).

356
357 Off-island movements were recorded for both Bali and Lombok. One movement event was
358 recorded between a small island (Nusa Penida) off the south-east coast of Bali and the surveyed
359 market Galiran. In Lombok, a single collector reported transporting birds between Lombok and
360 Sumbawa islands but did not involve direct movements to or from any of the surveyed markets.

361
362 **Discussion**
363 Live bird markets facilitate the movement of poultry through extensive networks that can span
364 large geographical areas (Soares Magalhães et al., 2010). Therefore, understanding trade patterns
365 and animal movements within live poultry marketing industries provides essential knowledge
366 concerning the likelihood of disease transmission by contact. Currently, this information remains
367 limited in Bali and Lombok and many other parts of Indonesia. The aim of this study was to
368 investigate the movement of live birds to and from selected live bird markets, which represented
369 the main types of markets found in Bali and Lombok, in order to identify the type and magnitude
370 of contacts that exist between live bird markets, poultry traders and poultry customers. From the
371 data collected in this cross-sectional study, two networks of contacts were constructed from
372 which descriptive analyses were carried out, enabling the identification of important
373 characteristics pertaining to network topology and key nodes within each network (Kiss et al.,
374 2006).

375
376 Findings from this study showed that whilst most respondents transported birds to and from
377 markets over distances of approximately 10 km, there were also traders and customers who
378 travelled much larger distances (in excess of 100 km) to buy or sell poultry. A study of poultry
379 trade networks in Cambodia found that middlemen (i.e. collectors) travelled further in pursuit of
380 collecting and trading poultry than retailers (i.e. vendors), who rarely sold poultry outside of
381 their home village (Van Kerkhove et al., 2009). This study found that traders typically travelled

382 greater distances than customers. The reasons why some traders and customers travelled large
383 distances to buy or sell poultry were not ascertained in this study. It is reasonable to assume that
384 traders may travel large distances to source poultry from specific locations (whether it be a farm,
385 market or other traders) or sell poultry where they know the demand is expected to be higher.
386 Explanations for the large distances travelled by some customers is however unclear. It could be
387 speculated that customers purchase poultry from a market close to their home for a family
388 celebration or religious ceremony that may be taking place in a distant location. Other factors
389 that may influence this behaviour are the availability or price of specific bird types. In traditional
390 Hindu culture (of Bali), different types of chickens and ducks (i.e. specific colours or physical
391 characteristics) are often required for different ceremonies (Mastika, 2007).

392
393 The identification of nodes with the most central positions in the network allows resources to be
394 specifically targeted towards those nodes for disease control programs, which is particularly
395 important in low-resource settings (Van Kerkhove et al., 2009). Degree centralisation indices
396 provide a measure of the number of incoming and outgoing movements for each node. Higher
397 values represent nodes with larger numbers of ties and these are therefore more likely to have a
398 greater influence in the network (May and Lloyd, 2001). In-degree can be thought of as a
399 measure of 'receptivity' or 'popularity' whilst out-degree measures 'expansiveness'
400 (Wasserman, 1994). In terms of disease transmission, nodes with high in-degree scores are more
401 likely to become infected due to the higher number of potentially infected birds entering the
402 node. High in-degree nodes may also be important 'disease spreaders' if they also have high out-
403 degree scores (Kiss et al., 2006). Therefore, it is important to identify nodes which have both
404 high in- and out-degree as these have the potential to act as 'super-spreaders' (Shen, 2004).

405
406 Both networks presented in this study had greater values for in- versus out-degree centralisation
407 and had more nodes with no incoming movements compared to outgoing movements. It is
408 important to note that these two findings are most likely the result of the disproportionate
409 number of traders (vendors and collectors) interviewed in this study, compared with customers
410 and therefore a greater proportion of nodes represent sources of poultry (i.e. outgoing or village-
411 to-market movements) rather than destinations (incoming or market-to-village movements).
412 Similarly, surveyed market nodes were expected to have higher degree (particularly in-degree)
413 than non-surveyed nodes due to the egocentric data collection approach employed in this study
414 that focused on markets.

415

416 Comparison of the two networks identified greater in- and out-degree centralisation indices for
417 the Lombok network compared to the Bali network. This finding is consistent with the highly
418 mobile nature of Lombok's poultry traders, who often source small numbers of birds from
419 several locations compared to Bali where traders generally source larger volumes from smaller
420 numbers of locations (Kurscheid et al, unpublished data). This finding indicates that high degree
421 nodes in the Lombok network play are likely to play a more dominant role in terms of disease
422 transmission compared to those in the Bali network. High degree nodes in both networks would
423 make ideal candidates for disease control programs (Albert et al., 2000), such as increased
424 surveillance (in terms of sampling and bird health checks), enhanced biosecurity measures (e.g.
425 bird zoning and daily cleaning of markets and cages) and education campaigns to increase
426 poultry traders' knowledge and awareness of HPAI and good biosecurity practices.

427
428 The importance of high-degree nodes within a network, in terms of disease dissemination, is
429 easily understood because, logically, individuals with a large number of contacts have the
430 potential to spread infection to a larger number of individuals (Bansal et al., 2007). However, the
431 extent of transmission through the entire network depends on the connectivity of the group to
432 which the individual belongs (Stark et al., 2006). Enhanced connectivity (cohesion) facilitates
433 disease dissemination throughout a network whereas fragmentation impedes it (Albert et al.,
434 2000). Despite the fact that details of live poultry movements were elicited from similar
435 proportions of respondents from each island and a similar number of nodes were present within
436 each network, the Lombok network contained 2.4 times as many directed links compared to the
437 Bali network demonstrating that the Lombok network is more connected than the Bali network.
438 Evidence for this was also provided by a number of other observed factors such as a larger
439 cohesion score, smaller values for fragmentation and average geodesic distance and a
440 substantially larger number and proportion of reachable pairs within the network. Therefore, it
441 appears that virus transmission would be more efficient in the Lombok network. The smaller
442 diameter of the Bali network indicates that fewer steps are required for the possibility of a
443 disease to reach any other node in the network compared to Lombok.

444
445 Betweenness indices reflect the influence an individual node has within a network. This
446 centrality measure represents the frequency with which a node falls between the shortest path of
447 other nodes and therefore indicates the amount of flow within the network that is controlled by a
448 particular node (Newman, 2003). High betweenness means that a particular node acts as a bridge
449 connecting otherwise unconnected nodes or groups (Wasserman, 1994). This is important in
450 terms of disease control because such nodes provide the bridge over which infection might travel

451 from one section of a network to another (Dubé et al., 2009). The fact that the normalised
452 betweenness centralisation index of Lombok was more than five times the value of Bali means
453 that a node in the Lombok network falls in the shortest path between two other nodes, on
454 average, five times more frequently than a node in the Bali network. It also indicates that bridge
455 nodes in the network play a greater role in controlling the flow of poultry through the Lombok
456 network compared to Bali. Furthermore, the Lombok network was the only one of the two that
457 was found to have a node with high total degree and betweenness (Figure 4). This node
458 (Narmada market) plays a key role in the network due to the large number of movements to and
459 from the market and its role as a bridge in the network. Furthermore, 40% of the 177 movements
460 recorded for the node were to and from unique contacts, meaning that it has a greater potential to
461 disseminate infection throughout the network than any other node within the Lombok network.
462 Despite this, the removal of this node (i.e. by closing down the market temporarily in the event
463 of an outbreak) would have little impact on the integrity of the network due to its high
464 connectivity. By way of contrast, removal of the node with the largest betweenness score in the
465 Bali network (Galiran market) would cause the main component of the network to fragment into
466 two sub-groups. Removal of one or, incidentally, both nodes with the highest degree would still
467 allow the integrity of the network to remain intact. Therefore, in the event of a reported outbreak
468 in Bali, closure of the market with the largest betweenness score would more likely limit the
469 ability of the virus to diffuse throughout the network compared to closure of other markets.
470 Although targeting the node whose removal partially collapses the network would be a priority
471 in an outbreak response scenario, all preventative, surveillance or control programs should also
472 include the two other highly connected nodes due to their influence and ability to disseminate
473 disease throughout the network (Shen, 2004). The absence of high degree and betweenness
474 nodes in the Bali network suggests that the roles of nodes within this network are quite distinct.
475 In summary, the higher degree and betweenness displayed by the Lombok network indicates a
476 network characterised by 'hubs' and 'bridges' whereas the Bali network is dominated more by
477 hubs alone.

478
479 Investigating the topological properties of a network allows us to identify whether the network
480 has random, small world or regular lattice properties (Dubé et al., 2009). Epidemic simulations
481 on theoretical networks have shown how the outcome of an epidemic in terms of size, speed and
482 pattern of diffusion may vary according to the topology of the network (Kiss et al., 2006;
483 Rushton et al., 2005). Whilst many real world networks typically display small world properties,
484 which are characterised by short geodesic distances and high clustering coefficients compared to
485 random networks of similar size (Telesford et al., 2011), neither of the networks in this study

486 showed these characteristics. However, both networks displayed right-skewed degree
487 distributions meaning that the majority of nodes have low degree whilst a small number, also
488 known as ‘hubs’, have high degree (Dezso and Barabási, 2002). Networks with right-skewed
489 degree distributions are important epidemiologically in terms of dissemination of disease and for
490 surveillance and control programs, largely because they tend to behave in a predictable manner
491 (Barabási and Bonabeau, 2003). Such networks are largely resistant to random control measures
492 because the vast majority of nodes have only a few links and their ‘removal’ has little impact on
493 the network (Albert et al., 2000). Therefore, there is a high probability that selected nodes will
494 have a low degree, causing only slight effects on the rest of the network, and hence, can tolerate
495 random ‘failures’ (or removal) of many nodes before they fragment (Barabási and Bonabeau,
496 2003). Networks with right-skewed degree distributions are highly susceptible to targeted
497 disease control programs because they rely on relatively few, highly connected hubs to maintain
498 connectivity (Albert et al., 2000). The presence of these highly connected or ‘bridging’ nodes
499 also makes the networks important for the propagation of epidemics as they can transmit disease
500 to many other nodes (Barabási and Bonabeau, 2003). Obviously the more ‘cohesive’ or
501 ‘connected’ a network is, the larger the potential for epidemic spread. Interventions to disrupt
502 spread are different. Random networks are moderately susceptible to targeted efforts or ‘attacks’
503 and there is little difference between random failures and targeted attacks in random networks
504 (Barabási and Bonabeau, 2003). Hence, targeted control strategies focusing on hubs within the
505 network can be very effective (Dezso and Barabási, 2002).

506
507 The availability of resources to investigate outbreaks and to control and prevent further
508 outbreaks is often limited in less-developed and developing countries, such as Indonesia. By
509 utilising knowledge of network characteristics, resources and investigational efforts can be
510 targeted toward markets and villages in central and influential positions within the network (Van
511 Kerkhove et al., 2009).

512
513 Currently, there are no formal documentation requirements in place to track movements of
514 poultry traders marketing birds through live bird markets in Indonesia. Therefore, in the event of
515 an outbreak authorities have limited information to direct them to other key markets and villages,
516 which may need to be notified or included as part of control activities. However, with knowledge
517 derived from a poultry movement network analysis similar to that described in this study,
518 markets connected to these villages can be closed and poultry farms and collector yards within
519 these areas can be notified and dealt with accordingly. Knowledge of potentially high risk

520 markets and villages will also allow authorities to target these for biosecurity improvements and
521 campaigns to raise awareness on good biosecurity practices.

522
523 Complete enumeration of contacts is normally required to create an entire network (Bansal et al.,
524 2007), however, given the large number of LBMs operating in Bali and Lombok it was not
525 feasible to conduct a census of all known markets as part of this study. Unfortunately this is
526 likely to have resulted in selection bias and the effects of this bias on the validity of network
527 statistical measures are difficult to quantify (Lockhart et al., 2010; Borgatti et al., 2006;
528 Costenbader and Valente, 2003). It is likely that inclusion of a greater proportion of contacts
529 would alter the connectedness of each network generated. The addition of new nodes may also
530 alter the centrality and consequently the roles that individual nodes played within each network.
531 However, it would be reasonable to assume that the type and level of bias would be similar
532 across both of the analysed networks (Lockhart et al., 2010). Therefore, appropriate inferences
533 can be drawn from this study by focussing on how the parameters for each network vary in
534 relative, rather than absolute terms. Previous studies have shown that there is little difference to
535 the robustness of centrality measures in the event of incomplete data due to either random
536 measurement error and missing data or deliberate sampling on nodes or edges, and that it is
537 reasonable to compute centrality indices when aware of these errors (Borgatti et al., 2006;
538 Costenbader and Valente, 2003; Marsden, 1993). Furthermore, market selection criteria
539 specifically aimed to ensure that key markets covering a broad range of districts in each island
540 were included, thereby increasing the potential scope of contacts, in an effort to capture as much
541 of the complete live poultry movement networks as possible in Bali and Lombok. Another
542 important point to note is that for the current study the number of movements to and from a node
543 (i.e. degree) was derived from survey respondents that provided details of source and destination
544 of birds. Given that a relatively small proportion of respondents did not provide this information
545 and that in some cases GPS locations of village names were not available and were therefore not
546 included in the analyses, it is likely that the calculated degree scores for each market slightly
547 under-represent the true number of movement events occurring to and from each site. The out-
548 degree, in particular, would likely be under-represented given the limited number of customers
549 interviewed for this study compared to traders. This was due to the focus of the study, which
550 primarily investigated the practices and behaviours of live poultry traders working in poultry
551 markets.

552
553 The marketing systems in Bali and Lombok rely heavily on the sale of live poultry through
554 markets and each step of the marketing chain involves a number of different players. Prior to

555 entering the markets, poultry may have changed ownership numerous times and if we associate
556 each exchange with a movement event, this amounts to a large number of movement events on
557 any given market day. Furthermore, findings from other studies (Soares Magalhães et al., 2010;
558 Van Kerkhove et al., 2009) indicate that festivals, religious celebrations and other special events
559 can result in a substantial increase in the magnitude of bird volume and trading frequency
560 occurring with a network. With such large numbers of birds and movement events occurring on a
561 daily basis through the highly complex networks identified in this study, it is not difficult to
562 envision the challenges faced by local authorities in HPAI related activities. Therefore,
563 identifying highly influential nodes within each network allows authorities to target HPAI
564 related activities to where they have better chance of success.

565
566 Throughout this study we refer to movements of 'live' poultry. It is important to point out that
567 not all bird movements occurring from markets are of live birds, as customers may have the birds
568 slaughtered prior to leaving the market. Although we did not specifically ask customers whether
569 they intended to have the birds slaughtered prior to leaving, we made the assumption that the
570 majority of birds purchased by customers leave the market alive. This assumption was based on
571 several findings from the survey: (1) only five of the 17 markets surveyed offered slaughtering
572 services in the market (all five of these markets were in Lombok); (2) only two of 134 customers
573 interviewed reported purchasing slaughtered poultry during their visit to the market; and (3) most
574 (64%) customers slaughter their own birds (either at the home or at a slaughter house).

575
576 Using the same study design and method for sampling vendors, collector and customers on Bali
577 and Lombok, we identified marked differences in the characteristics the networks generated for
578 each island. Further, we identified specific markets on each island that were likely to be highly
579 influential in the spread of disease (and therefore markets that should be targeted for surveillance
580 or enhanced biosecurity measures). Cross-sectional vendor-collector-customer studies, similar to
581 the study described in this paper, are required to identify LBMs with similar properties in other
582 areas of Indonesia.

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588

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593

593

594 **Author contributions**

595 Conceived and designed the study: JK, MS, SF and JT. Developed the questionnaire: JK, MA,
596 IA, SF and JT. Conducted the interviews: MA and IA. Analysed the data: JK, MS, PD and SK.
597 Drafted the manuscript: JK. Revised the manuscript: JK, MS, PD, SF, JT and SK.

598

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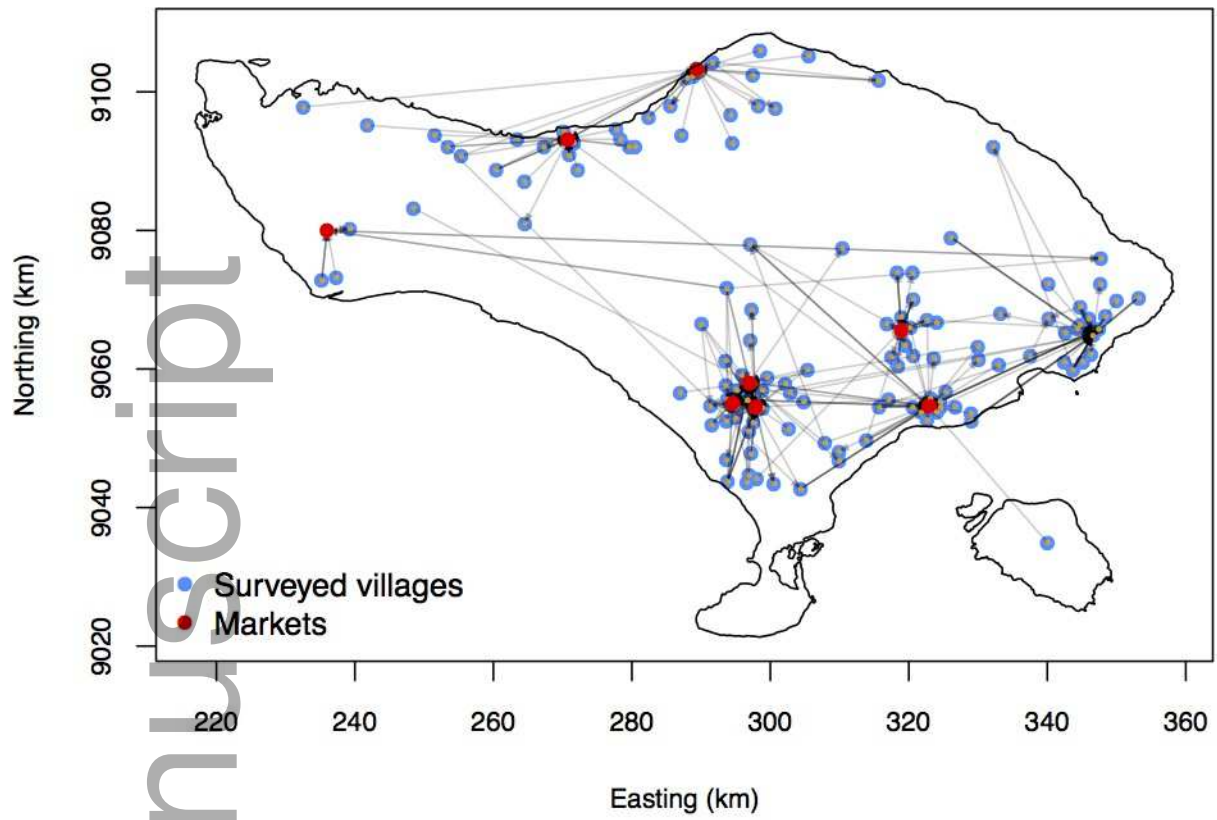
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705 **Supporting Information**

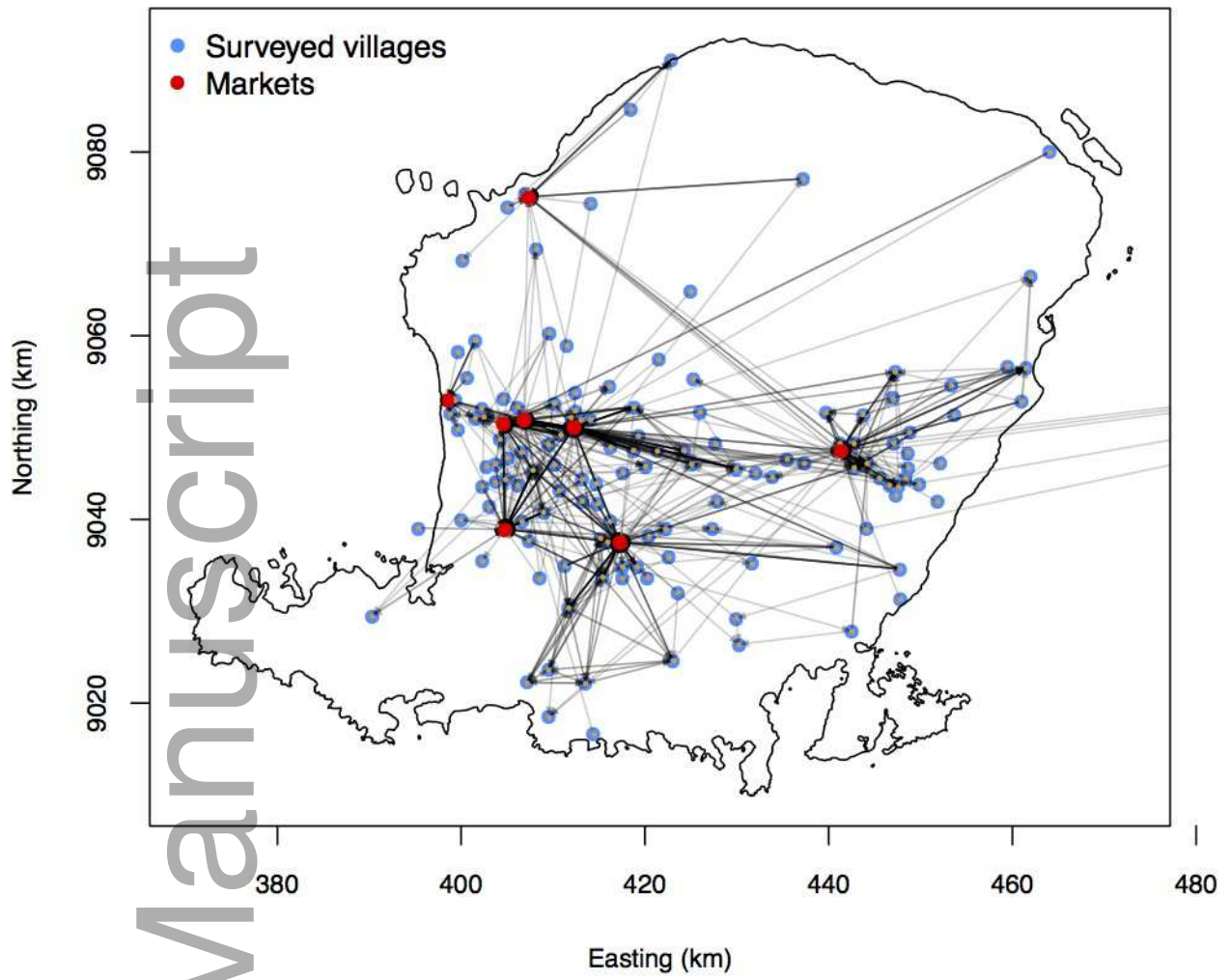
- 706 Figure S1. Names and locations of each of the $n = 9$ surveyed markets in Bali.
- 707 Figure S2. Names and locations of each of the $n = 8$ surveyed markets in Lombok.
- 708 Table S1. Movements occurring to and from each of the nine surveyed markets in Bali.
- 709 Table S2. Movements occurring to and from each of the eight surveyed markets in Lombok.
- 710 Table S3. Total number of respondents interviewed at each surveyed market in Bali and the
711 estimated number of each group of respondents frequenting each market on a typical day.
- 712 Table S4. Total number of respondents interviewed at each surveyed market in Lombok and the
713 estimated number of each group of respondents frequenting each market on a typical day.
- 714 Figure S3. Cumulative degree distributions for the Bali network.
- 715 Figure S4. Cumulative degree distributions for the Lombok network.
- 716 Figure S5. Box and whisker plot of market-to-village distances travelled in Lombok.
- 717 Figure S6. Box and whisker plot of village-to-market distances travelled in Lombok.
- 718 Figure S7. Box and whisker plot of market-to-village distances travelled in Bali.
- 719 Figure S8. Box and whisker plot of village-to-market distances travelled in Bali.
- 720 Figure S9. Box and whisker plot of market-to-village distances travelled by each respondent type
721 in Lombok.
- 722 Figure S10. Box and whisker plot of village-to-market distances travelled by each respondent
723 type in Lombok.
- 724 Figure S11. Box and whisker plot of market-to-village distances travelled by each respondent
725 type in Bali.

726 Figure S12. Box and whisker plot of village-to-market distances travelled by each respondent
727 type in Bali.

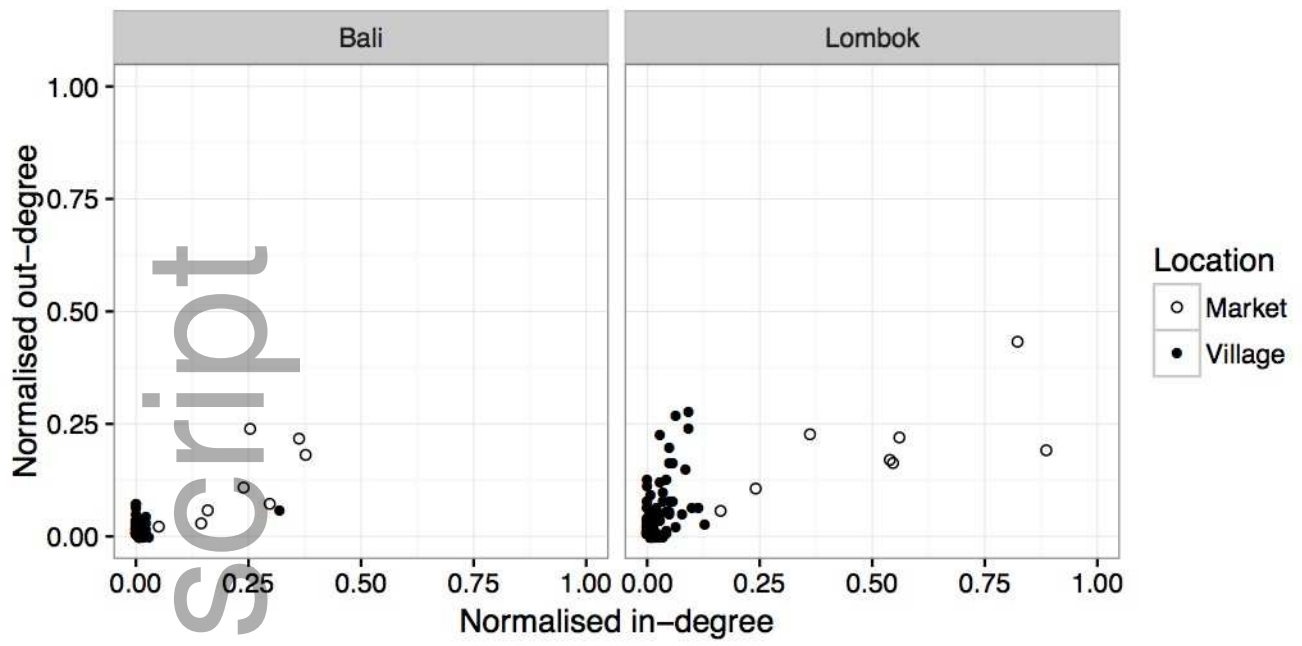
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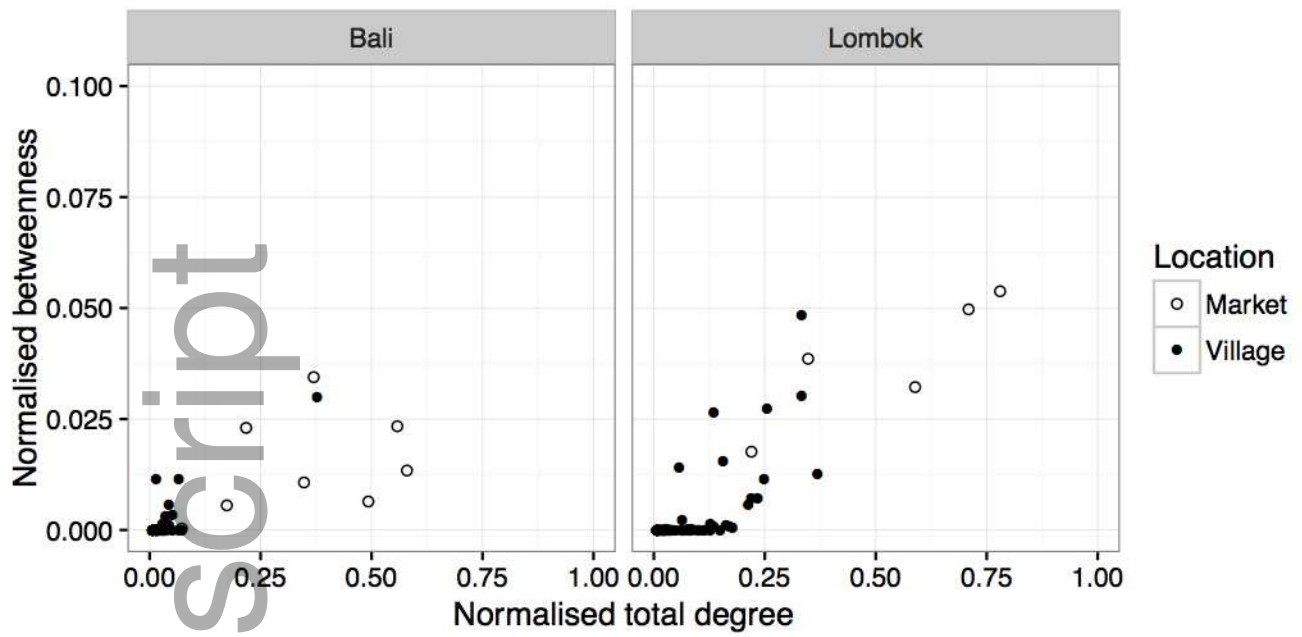


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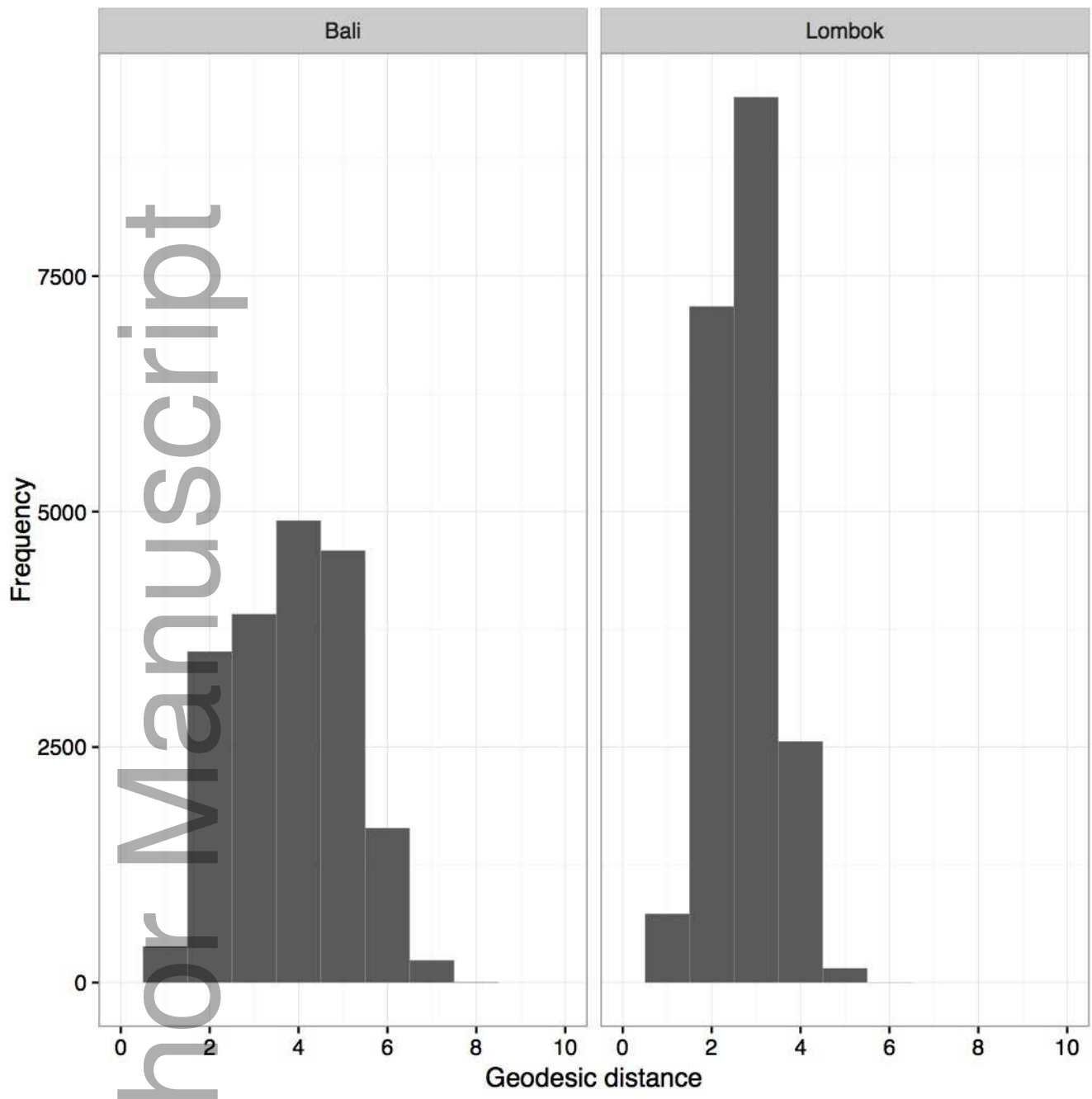
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