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Original article

NETWORK ANALYSIS OF LIVE PIG MOVEMENTS IN THE REPUBLIC OF NORTH MACEDONIA IN THE PERIOD 2019–2020: IDENTIFICATION OF KEY FARMS AND MUNICIPALITIES REGARDING THEIR ROLE IN THE SPREAD OF INFECTIOUS DISEASES

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Summary

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Social network analysis could be a useful tool in the understanding of many aspects of animal movements because the movement of pigs between farms is one of the main routes for the spread of infectious diseases. Its outputs may highlight information about pig farms and areas that are highly connected and identify key players in animal traffic. The purpose of the study was to identify key farms in the live pig movement network and detect municipalities in North Macedonia which are at risk of disease transmission due to increased pig movements. To this end, completed live pig movement data in the period 2019–2020 extracted from the electronic national database in the system of identification and registration of animals, from the Food and Veterinary Agency of the Republic of North Macedonia was used. Igraph package in R programming language was used to carry out the analysis and spdep package to test spatial autocorrelation. Our findings showed that the size of the network was 320 nodes and 859 links. It was found that 215 (67.2%) farms had in-degree values in the range 1−164 and 137 (42.8%) farms had out-degree values in range of 1−166. Twenty-four farms (7.5%) showed a betweenness centrality value of 1−72, and the cut-point analysis detected 56 farms (17.5%), with most farms located in central, east, and southeastern parts of the country. Network density showed 0.008 or 0.8% and clustering coefficient (transitivity) of 0.017. Moran's *I* statistic for spatial autocorrelation of municipalities with summarised in-degree showed negative value (−0.003, P=0.295) and municipalities with summarised out-degree showed positive value (0.126, P=0.031). This study identified pig farms that could influence the animal flow and their geographical location. The municipality of Veles was identified as the area with the highest arrivals and departures of pig batches. Findings may be useful to inform decision-makers to target farms and municipalities for surveillance and to organise official control and early detection of contagious swine diseases.

Key words: disease surveillance, movements, pig farm, social network analysis

INTRODUCTION

Network analysis investigates live animal movements and during the recent years its popularity in veterinary epidemiology is expanding (Dubé *et al.*, 2009; Wiratsudakul *et al.*, 2022).

The movement of pigs can be represented using a network where sourced or destinated farms of pigs represent nodes and links represent flows between them (Shi *et al.*, 2021). Moreover, the movement of pigs between holdings is an important path for disease spreading (Schulz *et al.*, 2017).

Furthermore, in veterinary science, the unit of interest (node) is either an animal or holding in terms of farm or collection centre and movements represent links, whereas each node and each link could be associated with one or more attributes (e.g. farm number or number of animals per farm). Therefore, social network analysis (SNA) as a tool could be useful to identify nodes central to animal flow production, which could be targeted to the design of surveillance systems and early detection of infectious diseases (Dubé *et al.*, 2008).

In the Republic of North Macedonia, farmers are obliged to identify pigs in all instances when they leave the holding, obtain an animal health certificate, and report in the system of identification and registration of animals as an authorised farmer or via a veterinary station within seven days following the event in accordance to Identification and Registration Law (Anonymous, 2012).

The Macedonian Food and Veterinary Agency has developed policies and measures against certain pig diseases by annual order of animal health, issued and updated annually, based on clinical examination, biosecurity assessment, categorisation on the farm level as well as sampling either on live and/or dead pigs and wild pigs.

Our study aims to describe and characterise the live pig movement network in the Republic of North Macedonia from 2019 to 2020 identifying farms and municipalities with a key role.

MATERIALS AND METHODS

Pig movement data from the 1st of January 2019 to the 31st of December 2020 were extracted from the electronic national database in the system of identification and registration of animals from the Food and Veterinary Agency of the Republic of North Macedonia. Two types of holdings were included in the extracted data: pig farms and animal markets. Only completed movements were considered in this study and created network was known as the "live pig movements network" (LPMN).

Direct movements to slaughterhouses as endpoints of pigs' life were not included in the present analysis (Nöremark *et al.*, 2011), furthermore such movement poses minor risk for farm-to farm disease transmission.

Data regarding other attributes such as the farm type or size or mode of transport were not available for this study. Manual extraction of coordinates of mapped farms was done from the national database after the analysis was carried out.

A network consists of two basic units: nodes and links. Nodes represent different entities according to the implemented field and links are lines between two nodes, showing relationships among them (Farine & Whitehead, 2015). In our study, each pig farm was represented with the node as a unit of interest and every

movement with a link where arcs are the direction of the links. A directed and unweighted network was used in our analysis.

Social network analysis was carried out with *igraph* package v. 1.2.5 in R programming language version 4.0.1 (R project for statistical computing), package *tmap* v. 3.1 was used for map municipalities with summarised in-degree and out-degree.

Spatial autocorrelation of municipalities with summarised in-degrees and municipalities with summarised out-degrees was analysed with Moran's *I* statistical test. It is defined as the relation between the values of a single variable. The Moran's *I* value ranges from -1 to 1 and measure correlation among neighbouring observations to find the patterns and the levels of spatial clustering among neighbouring districts (Boots & Gettis, 1998). It is analogous to Pearson's correlation coefficient. According to Moran (1950), the value of Moran' *I* will be positive if the neighbouring regions tend to have similar values, otherwise when the neighbouring regions have dissimilar values, it will be negative. The null hypothesis for the test is that municipalities with summarised in-degree or municipalities with summarised out-degree are randomly distributed, and the alternative hypothesis is that the municipalities are more spatially clustered than we would expect by chance alone. A permutation test for Moran's *I* statistic was calculated by using 999 Monte Carlo simulations for the given spatial weighting scheme to establish the rank of the observed statistic concerning the 999 simulated values. According to Bivand *et al.* (2022), these Monte Carlo hypothesis testing procedures provided a way to examine the distribution of the statistic of interest by exchanging at random the observed values between observations, and then comparing the simulated distribution under the null hypothesis of no spatial patterning with the observed value of the statistic in question.

Values of $P<0.05$ were considered statistically significant. The *spdep* package v. 1.1.5 in R programming language was used to perform the analysis.

The visualisation of pig farms locations was made in the QGIS Desktop open software v. 3.12.3.

The basic node and network SNA parameters were calculated: the size (number of nodes and links), in-degree, out-degree, node betweenness centrality, cut-point, edge density, and global clustering coefficient (transitivity) (Table 1).

A map of the country with municipalities was created after calculating in-degree and out-degree per farm and summarising obtained values according to their location in the municipality. This is in line with the organisation of veterinary inspection service which is based at the municipality level.

According to the Veterinary Health Law (Anonymous, 2007) the epizootiological unit represents an administrative area of the municipality and the epizootiology area consists of two or more neighbouring municipalities specified by the Director of Food and Veterinary Agency because of the implementation of veterinary health service of public interest.

RESULTS

The size of the live pig movements network consisted of 320 nodes and 859 links, whereas 99.7% (319/320) of nodes are farms and only one or 0.3% (1/320) is an animal market (Fig. 1).

In-degree centrality analysis detected 215/320 farms or 67.2% with in-degree

Table 1. Meaning of SNA metrics in this study

SNA parameters	Definition
SNA	The relationship among social entities and on the patterns and implications of these relationships (Wasserman & Faust, 1994).
LPMN	Directed non-weighted network of completed live pig movements from farm-to-farm, farm-to-animal market and animal market-to-farm from 2019 to 2020 in the Republic of North Macedonia.
Degree	The number of direct links of each node (Shi *et al.*, 2021).
In-degree centrality	The number of incoming connections (Shi *et al.*, 2021).
Out-degree centrality	The number of outgoing connections (Shi *et al.*, 2021).
Betweenness centrality	The number of shortest paths between all other nodes that go through a particular node. It measures the importance of a particular node as an intermediary in the network. A high value means good potential for animal movement flow in the network (Shi *et al.*, 2021).
Cut-point	The node whose removal from the network leads to an increase in the components and fragmentation of the network (Dubé *et al.*, 2011).
The density of the network	The proportion of links among all possible network links; ranges from 0 (all nodes are isolated) to 1 (all nodes are connected) (Nöremark *et al.*, 2011).
Clustering coefficient (transitivity)	Evaluates the average number of three nodes connected and measures how clustered the network is (Bellini *et al.*, 2020), and gauges the probability that adjacent nodes of a node are connected (Shi *et al.*, 2021).

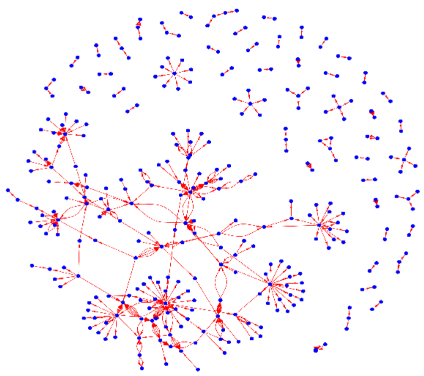

Fig. 1. Network visualisation of LPMN in the period 2019–2020. Blue dots correspond to farms and red arcs represent pigs' movements.

values within the range 1–164, and the rest of the farms 105/320 or 32.8% had zero in-degree value (Table 2, Fig. 2). The farms with the biggest in-degree values are located in municipalities Veles (VE) (farm code 510), Karbinci (KA) (farm code 279), Gevgelija (GE) (farm code 171), and Shtip (ST) (farm code 801) with 164, 158, 55, and 25 incoming batches respectively (Fig. 3).

Node out-degree analysis showed 137/320 or 42.8% of farms with values within the range 1–166, and the rest 183/320, or 57.2% were farms with zero outgoing connections (Table 2, Fig. 2). The farms with the highest values of out-degree were located in municipalities Gradsko (GR) (farm code 126), Sveti Nikole (SN) (farm code 844), Brvenica (BR) (farm code 211), and Berovo (BE) (farm code 199) with 166, 164, 45, and 42 outgoing batches respectively (Fig. 3).

Analysis with the Pearson coefficient of correlation of in-degree and out-degree

Table 2. Descriptive statistical values of SNA parameters and summarised values of in-degree and out-degree per municipality.

	Total	Min	Max	Mode	Median	Average	±SD
In-degree	320	0	164	1	1	2.7	13.3
Out-degree	320	0	166	0	0	2.7	13.8
Betweenness centrality	320	0	72	0	0	0.98	5.9
Municipality (sum in-degree)	80	0	208	0	0	10.7	34.2
Municipality (sum out-degree)	80	0	245	0	0	10.7	36.0

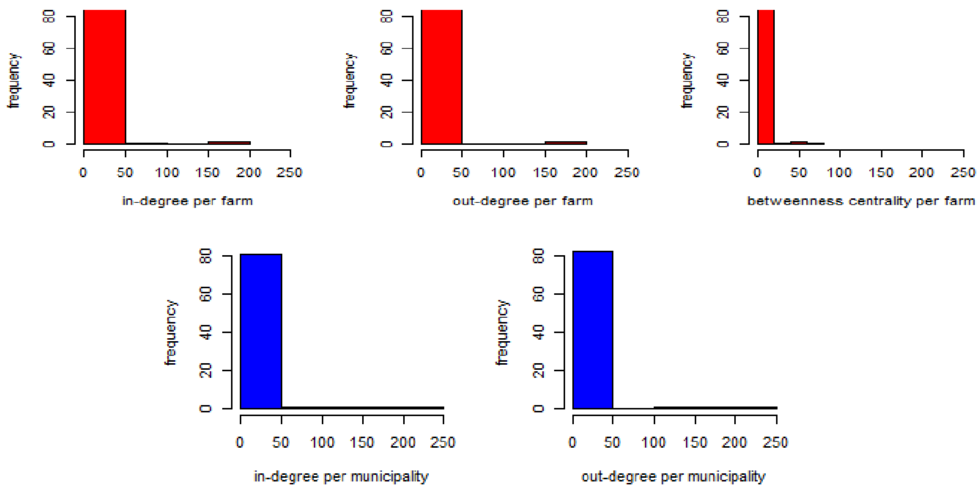

Fig. 2. Distribution of values of in-degree per farm, out-degree per farm, betweenness centrality per farm, in-degree per municipality, and out-degree per municipality.

values of farms showed a very weak negative correlation (r = –0.02).

Degree centrality values summarised per each farm according to their location in the municipality showed that 39/80 or 48.8% of municipalities in the country had sum in-degree within the range of 1–208, and the rest of the municipalities or 51.2 % (41/80) had zero in-degree. Municipality Veles had the biggest value of 208 received links, followed by Karbinci, Berovo, Gevgelija and Shtip with 186, 117, 56, and 45 respectively (Table 2, Fig. 2 and 3).

Furthermore, out-degree values summarised per each farm according to their location in the municipality showed that 27/80, or 33.8% of municipalities had out-degree between 1 and 245, and the remaining 53/80 municipalities (66.2%) had no outgoing links. Among them, the municipality of Veles showed the biggest total sum out-degree value of 245, followed by Gradsko, Berovo, Shtip, and Brvenica with 167, 118, 50, and 45 outgoing links (Table 2, Fig. 2 and 3).

A negative spatial autocorrelation in municipalities was observed with summa-

rised in-degree per farm (-0.003, P>0.05), and positive spatial correlation in municipalities (0.126, P<0.05) with summarised out-degree per farm (Table 3, Fig. 4).

Analysis of betweenness centrality of nodes detected 26/320 or 8.1% of farms with values from 1–72, and the rest of the farms 294/320 or 91.9% were detected with zero values (Table 2, Fig. 5A). The top five farms with the biggest betweenness centrality values were detected in different municipalities: Berovo (farm code 711), Strumica (SR) (farm code 052), Strumica (farm code 699), Shtip (farm code 479) and Berovo (farm code 083) with 72, 52, 44, 28 and 14 values respectively (Fig. 5A).

The cut-point analysis detected 56 out of 320 farms (17.5%) and they are marked according to their geographical location (Fig. 5B). Detected cut-point farms are located mostly in the municipality of Berovo followed by Veles, Vinica (VI), Pehchevo (PE), and Sveti Nikole (SN) with 15, 7, 5, 4, and 4 farms respectively (Fig. 5B).

The density of the network was 0.008 or 0.8% of all possible links and the transitivity or cluster coefficient (CC) was 0.017.

DISCUSSION

Our findings showed that the LPMN consisted of mostly farm-to-farm pig transfer. Although there are few animal markets in the country, only the animal market in Strumica was identified to be involved in

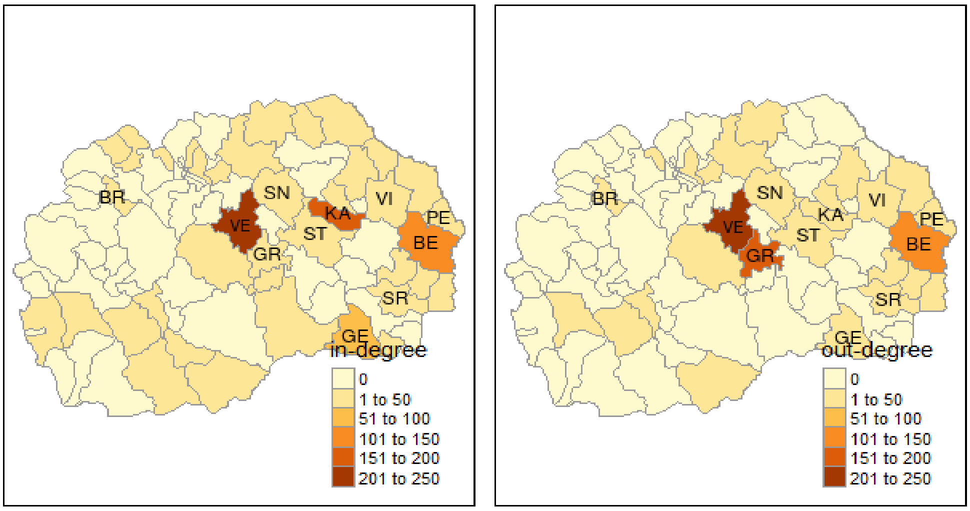

Fig. 3. Municipalities with summarised in-degree and out-degree per farm.

Table 3. Moran's *I* statistics with 999 Monte Carlo simulations of values of summarised in-degree and out-degree per municipalities

	Summarised in-degree per municipality	Summarised out-degree per municipality
Statistic	–0.003	0.126
Observed rank	705	969
P-value	0.295	0.031

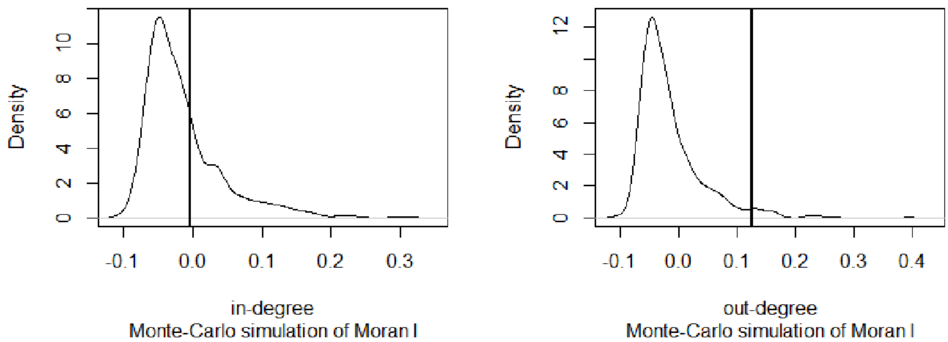

Fig. 4. Density plots of permutation outcomes. Left: values per municipality with summarised in-degree; right: values per municipalities with summarised out-degree. The vertical line represents observed Moran's *I* statistic.

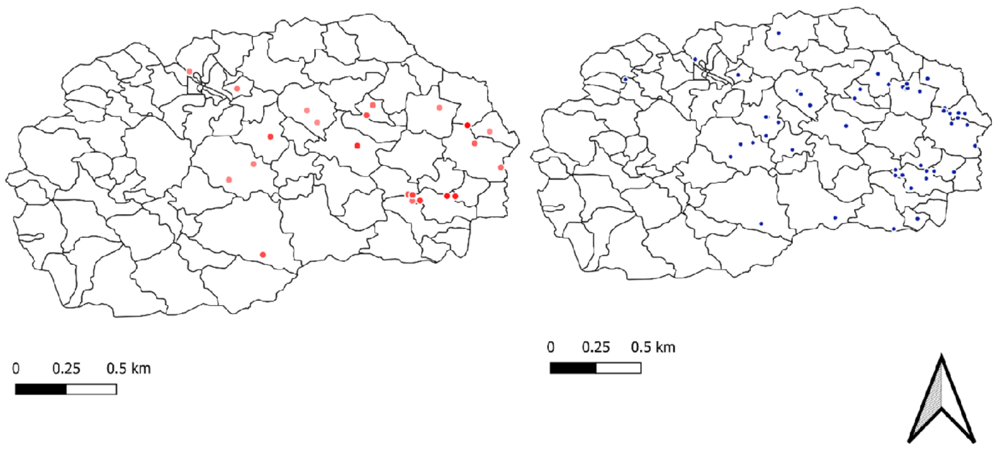

Fig. 5. Red dots represent 26 farms with betweenness values (1–72) from lower with a light colour toward bigger with dark colour **(A)**. Blue dots identified 56 cut-point farms according to their geographical location **(B)**.

the network. This observation is probably due to the farmers' behaviour to sell pigs out and/or nearby the market's locations avoiding taxes and consecutively those movements are unregistered or uncompleted. Additionally, in August 2019 North Macedonia closed animal markets for pigs as a preventive measure for the eventual introduction of African swine fever. Furthermore, the Covid-19 pandemic and the restriction of overall movements in 2020 were additional limitations (O'Hara *et al*., 2022).

Farm degree is simply a count of how many social connection (i.e. links) it has. The degree centrality for a farm is its degree and accurately tells who has a lot of social connections. The discrepancy in obtained values and right-skewed distribution of in-degree and out-degree per farm

in LPMN demonstrates the heterogeneity of the number of receipts and deliveries of pig baches, and consequently, their role in eventual disease spreading would differ greatly. It was observed that pig farms in LPMN with higher in-degrees tend to have lower out-degrees, suggesting that there are no farms that play the role of receivers and spreaders of disease at the same time, similarly as other animal movement study (Mekonnen *et al.*, 2019). The very low negative value of Pearson's coefficient of correlation between in-degree and out-degree per farm and the observation that farms with the biggest in-degree values are different than others with the biggest out-degree is in line with this consideration. Farms with many links can be called hubs and could catalyse infection dissemination (Mekonnen *et al.*, 2019; Menezes *et al.,* 2020). If disease occurred, they may be the most likely to introduce or disperse it. Because swine production structure and type of farms were not available for this study, we were not able go further with a more detailed analysis of the farms.

Detected and mapped pig farms in North Macedonia which showed betweenness values and identified cut-point farms were predominantly located in eastern and south-eastern parts of the country. Another study performed in North Macedonia, in the period from September 2019 to March 2020, identified the highest biosecurity risk scores in the pig farming sector and wild boar sightings in the eastern regions as well (O'Hara *et al.*, 2021). This could imply that farms in eastern regions of the country are potentially more at risk and target for disease surveillance, contingency plans and improved biosecurity measures.

Another study showed that farms with high betweenness values indicate a high frequency of animal movements through such farms (Noopataya *et al.*, 2015) and have the potential for animal flow (Poolkhet *et al.*, 2019) and consecutively could be places that may catalyse disease spread. In this study, 26 farms with different values of betweenness centrality were detected, but all have potential to link a group of farms. These farms are potentially the most suitable in terms of detecting strategic locations in the network for surveillance (Baron *et al.*,2020).

Identified cut-point in a network according to other authors seems to be suitable for surveillance and control (Noopataya *et al.*, 2015) and if the disease eventually spread in their area they could increase infectious farms. With efficient control of mapped 52 cut-point farms in possible disease outbreak, the significance of transmission can be minimised.

Very low network transitivity (CC) in LMPN means that more pig farms that were in direct contact with the same farms were not also in direct contact with each other, creating triangles in the network (Nöremark *et al.,* 2011). This probably implies that local farm-to-farm interactions are at a low level and eventually spreading of infective agents would be slow (Mekonnen *et al*, 2019).

Low values of CC and edge density in our LPMN is probably characterised by a random pattern, similar to findings in another study (Noopataya *et al*., 2015; Poolkhet *et al*., 2019) and eventually, transmission could be relatively slow (Keeling & Eames, 2005). In this case, targeting key actors and animal movement control is essential in the control of infection spreading (Poolkhet *et al*., 2019).

According to our results in North Macedonia municipalities with bigger in-degree are collectors and those with bigger out-degree values are pig distributors.

Furthermore, the right-skewed distribution of in-degree and out-degree values confirms this observation and suggests that municipalities are involved in pig-related activities of different intensity. If disease occurred, they may be the most likely to introduce or disperse it. It was observed that municipality Veles played a double role of receiver and spreader at the same time with the biggest values of summarised in-degree and out-degree. Nevertheless, in Veles no farms with betweenness centrality greater than zero were identified, but 7 cut-point farms and a farm with the biggest in-degree value there were detected, which implies that Veles could be potentially at higher risk of disease exposition. These findings could be useful in planning and prioritising preventive activities because state veterinary inspection service is organised in branch offices consisting of one or more municipalities.

Identifying key areas or farms is more successful to moderate pig disease than acting randomly (Li *et a*l., 2020). Analysis of spatial autocorrelation of municipalities with summarised in-degree showed a weak negative value near zero meaning that neighbouring municipalities had dissimilar values and the null hypothesis of random distribution was accepted. This could imply that the municipalities in North Macedonia are at random chance to receive pig batches and do not tend to cluster. On the other hand, spatial autocorrelation of municipalities with summarised out-degree showed a weak positive value which means that neighbouring municipalities had similar values: the null hypothesis was thus rejected and the alternative hypothesis that municipalities do not send outgoing pig baches randomly was accepted, implying that they tended to cluster.

Because only completed movements were taken into account, we should be aware of pig movements that are non-reported, undefined, or unconfirmed, and backyard farms could be unregistered. This could influence the dynamics of the network.

CONCLUSION

The results from this study could be useful to prioritise farms to inform decision-makers for disease surveillance, where mapped farms under potential risk may be targeted, surveyed or proper resources planned and used, bringing efficiency to the veterinary administration.

The municipality of Veles may be under the highest risk because it represents the area that received and delivered the most batches of live pigs.

Eastern and south-eastern territories of the country could be expected to be at a potential higher risk of introduction and/ or dissemination of disease pathogens due to the observed increased pig traffic and location of cut-point farms and farms with higher betweenness centrality

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