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Biosecurity measures in French poultry farms are associated with farm type and location

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ABSTRACT

The severe impact of recently reported Highly Pathogenic Avian Influenza (HPAI) outbreaks have emphasized the need to better monitor biosecurity practices among the different French poultry production systems. Between October 2016 and September 2018, a large national cross-sectional study was carried out in France to assess biosecurity levels in high-risk poultry farms and identify farm biosecurity profiles, using Multiple Correspondence and Hierarchical Cluster Analyses. Results indicate that there is substantial room for improvement in cleaning and disinfection, anteroom management and delimitation of farm and production units for more than 50 % of the 1,004 analyzed farms. The farm biosecurity profile showing the highest level of biosecurity included commercial intensive poultry farms (gallinaceous poultry farms, in North-Western France), and those with a recent history of HPAI outbreak (duck farms, in South-Western France). The farms biosecurity profiles showing the lowest level of biosecurity included farms with multiple species (duck and gallinaceous poultry) or multiple production types (broilers and egg-layers), located in regions with a lower poultry density and without a recent history of HPAI outbreak. Outcomes provide support to adapt biosecurity improvement and inspection plans.

1. Introduction

Within the European Union (EU), France is the largest egg producer (15 %) and the third largest poultry producer (11.4 %), with a poultry meat production of 1.7 metric million tons in 2018 (Eurostat, 2019). France is also the world's second leading duck producer (5.3 %), behind China, with up to 250,000 tons of meat duck per year (FAOSTAT, 2018). Specificities of the French poultry industry stem from the diversity of production systems (i.e. conventional, free-range, organic, etc.) and poultry species (i.e. broiler, turkey, duck, quail, etc.) that are spatially aggregated, with 70 % of the national production located in the western part of the country. Between 2015 and 2017, the French poultry industry was severely hit by unprecedented waves of highly pathogenic avian influenza (HPAI) outbreaks (Briand et al., 2018, 2017; Guinat et al., 2018), causing severe socio-economic losses for the poultry sector due to mass culling and restricted access to national and international trade. Between November 2015 and April 2016, 77 outbreaks of HPAI subtypes H5N1, H5N2 and H5N9 were reported in France. The following winter, between November 2016 and March 2017, 494 outbreaks of HPAI subtype H5N8 clade 2.3.4.4 were reported in France, while several other European countries also experienced severe outbreaks. The 'foie gras' duck industry, highly developed in the south-western part of the country, was particularly affected by these epidemics (Guinat et al., 2018). One of the main features of this industry is the common separation of growing farms (raising ducks up to 12 weeks of age) and fattening farms (from 12 to 14 weeks of age), leading to intense live duck transportation between the different types of production farms.

Biosecurity has been highlighted as a key component in the prevention of many important infectious diseases affecting poultry, such as HPAI (Garber et al., 2016; Gonzales et al., 2017; Guinat et al., 2020), infectious laryngotracheitis (Volkova et al., 2012), Newcastle Disease (Wiseman et al., 2018) and Salmonellosis (Snow et al., 2010). A number of external biosecurity measures (i.e. farm entrance design, flow of vehicles, management of dead birds and manure disposal, protection from wild birds, etc.) are applied to prevent pathogens from entering the farm while internal biosecurity measures (i.e. cleaning and disinfection,

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distinction between clean and unclean areas, etc.) help to reduce the spread of pathogens within the farm. Following the recent HPAI outbreaks, biosecurity has become a major concern for French veterinary authorities, with the publication of new regulations on biosecurity related to the poultry industry, both at farm and regional (during transportation) levels (DGAl, 2016a). Similar regulatory initiatives can be found in other countries, such as the National Poultry Improvement Plan in the United States (NPIP, 2021), with some programs targeting specific diseases - such as salmonellosis or campylobacteriosis (Koutsoumanis et al., 2020) - and/or programs associated with some production guidelines (British Lion Code of Practice, 2021).

However, it is unclear to what extent French poultry producers comply with on-farm biosecurity practices. Biosecurity gaps were identified within a small subset of poultry farms specialized in 'foie gras' duck production, prior to HPAI epidemics (Delpont et al., 2018). These gaps included the use of shared equipment, the absence of logbooks and non-functional anterooms. Several factors affecting compliance were suggested, including social pressure, perceived benefits of biosecurity and the level of farmer conscientiousness (Delpont et al., 2020). As these studies only focused on duck production, results could not be generalized to the other French poultry industries. In other countries, a number of studies have investigated biosecurity on poultry farms. However, most of them have focused on a specific location and/or a specific epidemic context (Dorea et al., 2010), have involved a low number of farms (Gelaude et al., 2014; Scott et al., 2018) or a single type of poultry production (Huang et al., 2017; Tanquilut et al., 2020a, 2020b; Van Limbergen et al., 2018).

In order to verify whether poultry farms adopted the new regulations, the French veterinary authorities launched biosecurity audits in January 2016.

Given the important socio-economic impact of recent HPAI outbreaks to the poultry sector, the objective of this study was to describe biosecurity practices among different poultry production systems in France, using veterinary authorities' inspection reports, and to identify farm biosecurity profiles. Data generated by these audits may help adapt biosecurity management plans and also offer considerable opportunities for research, providing a baseline assessment of biosecurity practices and enabling the identification of practices related to higher risk of poultry infectious disease incursion and spread at the national level.

2. Materials and methods

2.1. Farm selection

Reports from 1,472 on-farm visits were obtained as part of a large national campaign conducted by the French veterinary authorities to evaluate the level of adoption of biosecurity practices in poultry farms, following the HPAI outbreaks (between October 2016 and September 2018). Selected farms resulted from a targeted sampling of poultry farms carried out by local veterinary authorities, based upon an assessment of the level of risk of HPAI infection. The risk assessment took into account the following criteria: (i) having a history of HPAI in the farm, (ii) being close to a hatchery or a breeder farm (iii) producing ducks (or geese), alone or in combination with other poultry, since they were the most affected species by the HPAI epidemic (Briand et al., 2018), (iv) being located in a zone with a high density of poultry farms (Fig. 1), (v) being located in a zone with a high density of wild birds. Sample size was defined by governmental guidelines (DGAl, 2016b). All selected farms were visited, as it was a government requirement. When the inspectors identified critical biosecurity breaks at a farm, some "follow-up visits" could be carried out.

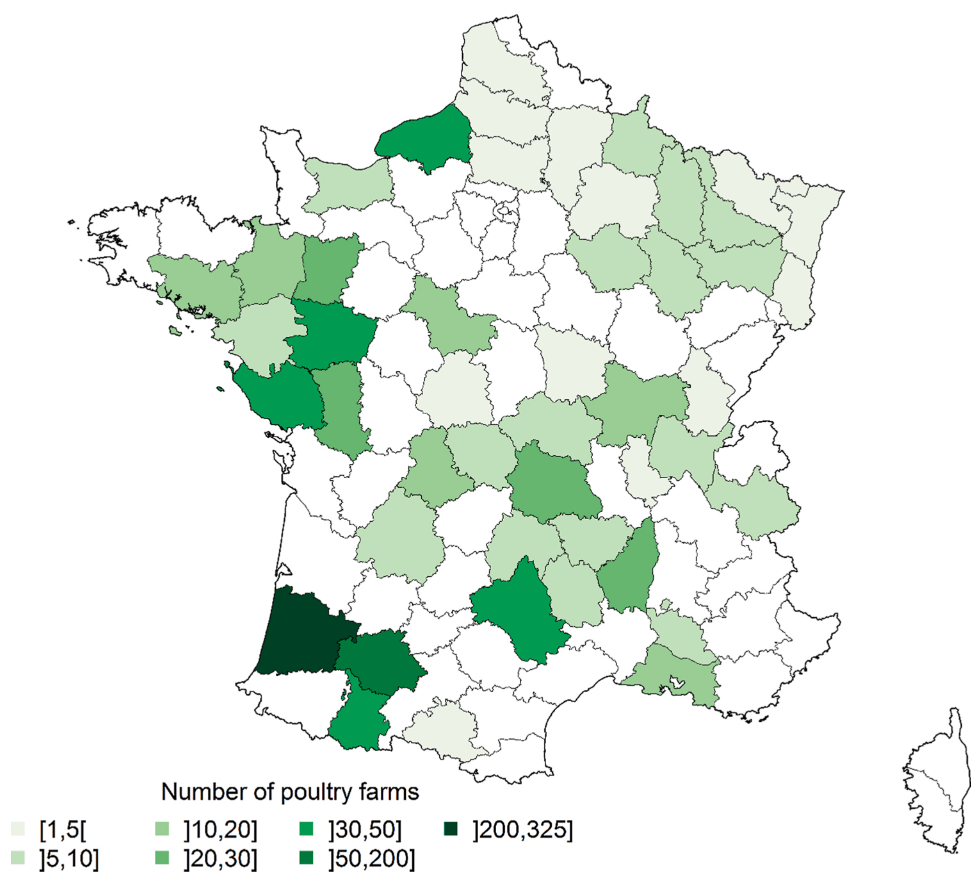

Fig. 1. Spatial distribution of the 1,004 poultry farms visited during the cross-sectional study on biosecurity compliance, between 2016 and 2018.

2.2. Biosecurity practices

Data on biosecurity practices were collected through face-to-face questionnaires with the farm owner - who is also the farm manager in most French poultry farms, given their small size. The questionnaires were filled by official veterinary inspectors, during a visit on the farm. The visits lasted approximately one hour and - depending on the questionnaire items - consisted of checking farm records (e.g. presence of a biosecurity formation certificate), making direct observations of the farm premises (e.g. anteroom setting and equipment) and interviewing directly the farm owner (e.g. daily removal of carcasses). All inspectors stemmed from local veterinary authorities and two inspectors were present during each farm audit. The inspectors had received specific training in biosecurity and the questionnaire was accompanied by an interview guide, which aimed at standardizing data collection. Inspectors were either veterinarians or veterinary technicians, and although these personnel did not have the same educational background, they had received the same training in biosecurity assessment. The questionnaire consisted of 47 closed questions, covering internal and external biosecurity items. Responses, which were initially coded into four scores, from A (adequate) to D (major inadequacy), were recoded into binary variables: adequate (score A) and inadequate (scores B, C and D) in order to clearly differentiate farms following regulations from others. The total number of variables initially present in the questionnaire (n = 47) was reduced after merging variables related to the same topic. Indeed, the initial questionnaire was designed to deal with a wide variety of farm layouts, leading at times to a few questions addressing the same issue. For example, the variable "training in biosecurity" encompassed two questions regarding biosecurity training certificates for farmers and farm employees. Also, variables with too numerous missing data were removed (i.e. when more than 6.5 % of farms lacked data). The final list of nine variables considered in this study is presented in Table 1. Additional data were also collected on farm characteristics (species, type of production and location). "Species" included farms producing only commercial waterfowl (ducks and geese are thereafter referred to as "ducks"), only gallinaceous poultry (chicken, turkeys and minor species such as guinea fowl or quail) or both commercial waterfowl and gallinaceous poultry (referred to as "mixed"). "Type of production" referred to the various stages of 'foie gras' production, meat duck production, breeder farms, egg-layers, meat-type gallinaceous poultry and finally farms combining different types of production. "Location" included: "Northwest" (comprising Bretagne, Pays-de-la-Loire, Normandie and Poitou-Charentes regions), "Southwest" (comprising Aquitaine and Midi-Pyrénées regions), and "Other" (comprising the rest of the territory), representing the main poultry production areas based on poultry farm density distribution (Fig. S1). A variable combining "location" and "species" (referred to as "species, by region") was produced in order to distinguish poultry industries (with a different history and culture) within a same production area. The two variables on farm characteristics considered in this study are presented in Table 2. The full questionnaire is available in French (DGAl, 2017).

2.3. Data analysis

The relationships between the biosecurity variables were first described using a Multiple Correspondence Analysis (MCA) (Dohoo et al., 1997). MCA is an exploratory technique which allows the representation of the different variable categories as points in a low-dimensional space, using synthetic axes (or factors). The more variable categories are associated, the closer they are plotted to each other and the more frequently variable categories are recorded, the closer they are plotted to the origin of the axes. Farm characteristics were included as supplementary variables, meaning that they did not influence the analysis but were used to interpret the results. Farms sharing similar biosecurity practices were then aggregated into clusters (or profiles) according to the results of the MCA, using a Hierarchical Cluster Analysis (HCA), based on Ward's method. The over-representation of variables within each cluster (i.e. the identification of variables which best describe each cluster) was computed with a hypergeometric test (Husson et al., 2017). The analysis was implemented in R software (R Core Team, 2011) using the *FactomineR* package (Le et al., 2008).

Table 1
Description of the nine variables related to biosecurity practices, from a cross-sectional study in 1,004 French poultry farms visited from 2016 to 2018.

Variable name	Description	Number of farms (%)
Biosecurity plan	Presence of all the components of the biosecurity plan, regardless of their quality: detailed map of the farm including its zones, list of all expected movements (people, vehicles, etc.), decontamination protocol, pest management protocol, manure and carcass disposal protocols, wild bird management protocol, training certificates, visitor log, poultry delivery and catching certificates, biosecurity self-testing records and non-commercial poultry keeping statement.	709 (70.6)
Training in biosecurity	Farmer and employees have a biosecurity training certificate	843 (84.0)
Delimitation of farm and units	Adequate definition and actual delimitation of zones within and around the farm (sheds and outdoor range, professional zone, public zone), with signs, fences, chains, etc.	622 (62.0)
Management of vehicle movements	Presence of a traffic map reporting movements of vehicles in the different zones (identification of intersection of movements in time or space, putative entry of the rendering truck within the farm, etc.)	735 (73.2)
Anterooms	Adequate anteroom location, conformation (clear distinction of at least two zones) and equipment (should allow proper handwashing and changing of boots and overalls)	627 (62.5)
Cleaning and disinfection	Existence of an updated cleaning and disinfection protocol, sheds are in a condition which allows proper decontamination, easy access to ventilation, feeding, watering and manure disposal systems	509 (50.7)
Clear area around poultry units	The area around poultry sheds is clear of useless material, food spillage and vegetal overgrowth	801 (79.8)
Pest management protocol	Existence of an updated rodent management protocol (location of baits, recording of bait consumption)	654 (65.1)
Downtime	Downtime durations are respected	784 (78.1)

3. Results

A total of 1,472 inspections reports from October 2016 to September 2018 was obtained. In this study, only one report was taken into account for each farm and 97 follow-up visits were thus discarded. Another 102 reports were discarded as they did not provide information on farm characteristics. Moreover, as MCA does not allow missing data, 269 reports also had to be discarded due to missing data. A total of 1,004 inspection reports were finally analyzed. The farms visits were carried out over approximately 22 months but more than 90 % of the analyzed farm visits were carried out in a 10 month-period (between March 2017 and January 2018). Around 6% of analyzed farm visits took place during the French 2016–2017 HPAI epidemic, with 39 % of these being gallinaceous poultry farms from the "other" regions.

Most of the farms were located in the "Southwest" (514/1004, 51.2

Table 2
Description of the two variables related to farm characteristics, from a cross-sectional study on biosecurity practices in 1,004 French poultry farms visited from 2016 to 2018.

Variable name	Number of farms (%)
Production type	
'Foie gras' ducks: fattening stage	163 (16.2)
'Foie gras' ducks: growing stage	180 (17.9)
'Foie gras' ducks: both stages	167 (16.6)
Meat ducks (i.e., non-related to 'foie gras' production)	18 (1.8)
Mixed: ducks (meat ducks or 'foie-gras' ducks) and gallinaceous poultry*	81 (8.1)
Mixed: meat-type gallinaceous poultry* and egg-layers	39 (3.9)
Meat-type gallinaceous poultry* (i.e., egg-layers are excluded)	207 (20.6)
Egg-layers	99 (9.9)
Breeders (reproduction)	50 (5.0)
Species, by region	
Gallinaceous poultry*, "Southwest"	57 (5.7)
Gallinaceous poultry*, "Northwest"	79 (7.9)
Gallinaceous poultry*, "Other**"	218 (21.7)
Ducks, "Southwest"	423 (42.1)
Ducks, "Northwest"	87 (8.7)
Ducks, "Other**"	41 (4.1)
Mixed (both ducks and gallinaceous poultry*), "Southwest"	34 (3.4)
Mixed (both ducks and gallinaceous poultry*), "Northwest"	12 (1.2)
Mixed (both ducks and gallinaceous poultry*), "Other**"	53 (5.3)

* Gallinaceous poultry refers to chicken, turkey, guinea fowl or quail.
** "Other" refers to the zone which neither comprises Southwest nor Northwest.

%), followed by "Other" (312/1004, 31.1 %) (Fig. 1 and Table 3). Most of the farms were raising 'foie gras' ducks (510/1,004, 50.8 %), followed by meat-type gallinaceous poultry (207/1,004, 20.6 %) and egg-layers (99/1,004, 9.9 %). Among the biosecurity variables, "training in biosecurity" showed the highest level of reported adoption (843/1,004, 84.0 %) (Table 3), followed by "clear area around poultry units" (801/1,004, 79.8 %) and "downtime" (784/1,004, 78.1 %). Conversely, "cleaning and disinfection" showed the lowest level of reported adoption (509/1,004, 50.7 %), followed by "delimitation of farm and units" (622/1,004, 62.0 %) and "anterooms" (627/1,004, 62.5 %).

The MCA was conducted on the six first factorial axes, accounting for 83.5 % of the variance. The HCA analysis resulted in the identification of four groups (or clusters) of farms based on their biosecurity level (Table 3). Most farms were classified as cluster 1 (529/1,004, 52.7 %). Overall, farms in cluster 1 showed the highest reported level of adoption of biosecurity practices, with 9/9 adequate practices which were over-represented (meaning that they had a statistically higher percentage of adequacy than the average). Cluster 1 included a majority of duck farms located in the Southwest (294/529, 55.6 %). To a lesser extent, this cluster was also characterized by gallinaceous poultry farms located in the Northwest (50/529, 9.5 %). Farms in cluster 2 and 3 showed an intermediate reported level of adoption of biosecurity practices, with respectively 2/7 and 2/9 adequate practices which were over-represented. In cluster 2, 2/9 adequate practices were neither over- nor under-represented. Farms in cluster 2 had a higher reported level of adoption of biosecurity practices than in cluster 3, as in cluster 3 adequate practices were more often or more strongly under-represented (7/9 practices). Cluster 2 (141/1,004, 14.0 %) was characterized by duck farms, predominantly located in the Southwest (71/141, 50.4 %) and to a lesser extent in the Northwest (25/141, 17.7 %) regions. However, duck farms located in the Southwest region were less represented in cluster 2 than in cluster 1 and duck farms located in the Northwest region were overall more represented in cluster 2. Cluster 3 (210/1,004, 20.9 %) was predominantly characterized by gallinaceous poultry farms located in "Other" region (73/210, 34.8 %), and, in terms of production type, by meat-type gallinaceous poultry (62/210, 29.5 %). Overall, farms in cluster 4 (124/1,004, 12.4 %) showed the lowest

Table 3
Results of the hierarchical clustering analysis (HCA) performed on the multiple correspondence analysis (MCA), from a cross-sectional study on biosecurity practices in 1,004 French poultry farms visited from 2016 to 2018. No data is given when the variable is not statistically over- or under-represented in a group (hypergeometric test, p.value > 0.05).

Variable	Cluster 1 (n = 529) % in the cluster	Cluster 2 (n = 141) % in the cluster	Cluster 3 (n = 210) % in the cluster	Cluster 4 (n = 124) % in the cluster	total %
Biosecurity variables					
Biosecurity plan	96.2	–	41.0	19.4	70.6
Training in biosecurity	93.8	97.2	100.0	0.0	84.0
Delimitation of farm and units	86.2	48.9	33.3	21.8	62.0
Management of vehicle movements	95.8	64.5	48.1	29.0	73.2
Anterooms	87.9	46.8	33.3	21.0	62.5
Cleaning and disinfection	83.2	22.0	10.0	13.7	50.7
Clear area around poultry units	97.9	0.0	96.7	64.5	79.8
Pest management protocol	92.2	47.5	29.5	29.8	65.1
Downtime	99.1	–	51.0	35.5	78.1
Farm characteristics					
Production type					
'Foie gras' ducks: growing stage	20.2	27.0	8.6	–	17.9
'Foie gras' ducks: fattening stage	18.5	22.7	–	6.5	16.2
'Foie gras' ducks: both stages	20.2	–	–	8.1	16.6
Meat ducks	0.9	–	–	–	1.8
Mixed: ducks and gallinaceous poultry	5.5	–	11.9	14.5	8.1
Mixed: meat-type gallinaceous poultry and egg-layers	0.8	–	9.5	8.9	3.9
Meat-type gallinaceous poultry	–	13.5	29.5	–	20.6
Egg-layers	–	2.8	–	16.1	9.9
Species, by region					
Gallinaceous poultry, "Other"	15.7	11.3	34.8	37.1	21.7
Gallinaceous poultry, "Northwest"	9.5	–	–	–	7.9
Mixed (both ducks and gallinaceous poultry), "Other"	2.3	1.4	9.5	15.3	5.3
Ducks, "Other"	1.7	–	7.6	9.7	4.1
Ducks, "Northwest"	4.9	17.7	–	16.1	8.7
Ducks, "Southwest"	55.6	50.4	21.4	10.5	42.1

reported adoption of biosecurity practices, with 9/9 adequate practices which were under-represented. As in cluster 3, cluster 4 was predominantly characterized by gallinaceous poultry located in the "Other" region (46/124, 37.1 %), but in terms of production type, cluster 4 was predominantly characterized by egg-layers (20/124, 16.1 %). More generally, cluster 3 and 4 were rather well characterized by farms located in the "other" region and included a relatively high proportion of "mixed" production types.

4. Discussion

This study provides adoption rates of observable biosecurity measures in high-risk French poultry farms and proposes four farm profiles, based on farm structure and protocols. The biosecurity profiles are linked with specific poultry production types, species and region.

The sampling frame of this study is not representative of all poultry farms in France. It originates from an audit tool aimed at enforcing the proper application of biosecurity measures on high infection risk farms in the context of unprecedented epidemics of HPAI. For that reason, a non-random sampling targeting these high-risk farms was obtained. To achieve this, a number of farm characteristics associated with higher risk of HPAI infection were listed in order to help local veterinary authorities perform their sampling. However, given the spatial heterogeneity in poultry production, these inclusion criteria could not always be met. For example, in many departments from "other" regions, there are only a few duck farms, there is no history of avian influenza and the density in duck farms is low. Therefore, the inclusion criteria were different among French regions, in spite of sharing a similar objective. However, as MCA and HCA capture the variability within a dataset, the identification of profiles (linked with type of poultry and region) should have been similar with a random sampling. Considering that the 1,004 inspection reports involved on-site visits, this study provides data on a high number of farms and therefore a valuable overview on the degree of adequate biosecurity structures and protocols observed in various farm types and regions of France. Studies on biosecurity that involved on-site visits usually include a lower number of farms (64–339) (Delpont et al., 2018; Huang et al., 2016; Scott et al., 2018; Van Limbergen et al., 2018; Van Steenwinkel et al., 2011) by contrast to phone interviews (1,715 farms; East, 2007). The participation rate was 100 % since farm inspections were compulsory, as they were performed by veterinary authorities. As a consequence, selection bias is not an issue. Numerous inspection reports were discarded because of the fact that MCA and HCA do not accept missing data (n = 269, with regards to biosecurity data). However, we have evidence (Figs. S2 and S3) that the identified profiles would share the same characteristics and lead to the same conclusions. The time interval of the inspections was wide and included the 2016–2017 H5N8 epidemic. The level of biosecurity compliance would be expected to be higher after the epidemic (Roche et al., 2019) and thus have an effect on the construction of the profiles. However, we believe that the construction of the profiles remained unaffected because (1) more than 90 % of the analyzed farm visits took place in a much narrower time interval after the epidemic and (2) because the farm type predominantly visited during the epidemic did not show a major increase in biosecurity compliance after the epidemic.

It is difficult to assess effective compliance with biosecurity measures (i.e. the proportion of times that a given measure is correctly applied), as routine biosecurity measures cannot be properly assessed, unless cameras or tracing devices are installed on farms (Racicot et al., 2011). Such tools can only be used for research purposes, on a low number of farms, since it is time-consuming to have a person analyze the video footage. To our knowledge, no video analysis software was developed so far for that purpose. However, data obtained during farm visits may be more reliable than in postal or telephone questionnaires, as direct observations provide a more objective assessment of farm biosecurity (Nespeca et al., 1997). In this study, different sources of information were used: formal observations, verification of farm-records and questions asked to the farmer. The questions which only relied on farmer statements may lead to inaccurate answers on the part of some respondents, more importantly considering of the formal aspects of these inspections by veterinary authorities. The high number of inspectors involved with biosecurity auditing may introduce a bias related to differences in thoroughness of inspection of various biosecurity practices between inspectors. Indeed, not all inspectors had the same knowledge of poultry farming (depending on the local abundance of poultry farms). Also, not all inspectors were veterinarians. However, as mentioned above, to prevent this, the inspectors were given inspection guidelines and received the same biosecurity training before the onset of the inspection campaign. The questionnaire was designed to fit several types of production while some biosecurity measures are type-specific. As a consequence, some variables had to be removed as numerous missing data could not be avoided. For example, variables related to the management of outdoor ranging areas were not assessed in this study, as the study population also included farm types which do not provide outdoor access. Such variables could be included for the construction of the farm profiles in a specific analysis conducted on free-range farms only. Also, the information on the presence or absence of an outdoor range would enrich the analysis of the profiles constructed in the present study. Although it is possible to infer from breeding techniques and production statistics that many broiler farms in South-West and all 'Foie gras' duck farms (growing stage) involve an access to an outdoor range (FranceAgriMer, 2015), there are no such possible inference for broiler farms in other regions, nor for egg-layer farms. The management of an outdoor range is a challenge with regards to prevention of disease introduction from wild birds. Free-range poultry farming was associated with a higher risk of infection by avian influenza (Artois et al., 2009), in particular when water bodies – which attract wild birds – are located close to the farm (Bouwstra et al., 2017). Apart from the inadequacy of the audit questionnaire to adapt to some specific farming conditions, some missing data could have been avoided. Providing the inspectors with additional training on the inspection procedures would likely have allowed the investigation of more biosecurity variables.

Among the 1,004 farms, the variable which showed the highest rate of reported adoption was "Training in biosecurity". This result is not surprising since this training is compulsory and requires little investment (usually a day-long training and attendance fees were supported by various organizations). Concerning the farmers who did not comply, as the first official training sessions in biosecurity only started in 2016 (shortly after the publication of the new biosecurity regulations), it is possible that they had already planned to attend such workshops by the time they were inspected. The training sessions in biosecurity were similar for all farmers over the whole French territory and similar training certificates were issued. The training sessions consisted of a theoretical part (transmission pathways for avian influenza and basics of biosecurity in poultry farms) and a practical part where farmers would each discuss their own situation and find adapted solutions. The theoretical part used the same documents for all training sessions but the content of the practical part was specific to each training session, as it depended on the participants and the expertise of each instructor. Although knowledge in biosecurity is necessary (Delpont et al., 2020), it may not be sufficient for the effective application of biosecurity measures. In a study conducted among poultry catchers, knowledge in biosecurity was satisfactory but the catchers explained that they did not perform the biosecurity measures because they were not given enough time to do so (Millman et al., 2017). Overall, 70.6 % of farmers had a comprehensive biosecurity plan for their farm (i.e., all components were present, regardless of their quality). Similarly, in Australia, this item presented rates of adoption between 50 and 100 %, depending on the type of poultry (Scott et al., 2018). Two of the variables with the lowest level of reported adoption, namely "anterooms" and the "delimitation of farm and units", refer to the concept of separating specific zones, both within the farm and with the outside. Inadequate "Delimitation of farm and units" was recently found to be positively associated with a previous HPAI infection in duck farms (Guinat et al., 2020). Although the separation of zones is one of the key principles of biosecurity (Dewulf et al., 2018), it is not often well understood in practice by farmers. The complexity of applying proper anteroom biosecurity measures (including the proper separation of zones) was demonstrated in a study reporting a total of 44 different biosecurity errors related to broiler and turkey barn anterooms (Racicot et al., 2011).

This study distinguished four groups of farms according to their level of biosecurity. Results showed that farms with the highest level of biosecurity (cluster 1) were mainly mule duck farms located in the southwest of France. Since this type of farm was the most affected by the HPAI outbreaks (Briand et al., 2018; Napp et al., 2018), this result may indicate that having experienced HPAI outbreaks is likely to lead farmers to improve the structural layout of their facilities in order to apply biosecurity measures and to have proper protocols in place. We considered here that the whole Southwest area did experience the outbreaks, as strict control measures were implemented in the area (poultry movement restrictions, culling of healthy flocks, temporary ban on duck production). The effect of disease experience on the adoption of biosecurity measures was also described in a different context: in poultry farms in Georgia, USA, biosecurity measures were more respected in the area where outbreaks of infectious laryngotracheitis occurred (Dorea et al., 2010). A possible explanation for the effect of disease experience on biosecurity is that of an increase in risk perception (Garforth, 2015). The high level of reported adoption of biosecurity measures in gallinaceous poultry farms located in the "Northwest" region may be due to experiencing more endemic diseases, such as infectious bronchitis, as it is the region with the highest poultry-farm density (Fig. S1) and the risk of farm-to-farm transmission is therefore more important (Bonney et al., 2018; Fernandez, 1995; Franzo et al., 2020). Also, the fact that it is a highly integrated industry may increase the availability of technical advice in the field of biosecurity (Cui et al., 2019; Niemi et al., 2016). The presence in low-biosecurity clusters (clusters 3 and 4) of mix production farms may be linked to a lower degree of specialization and technicity by the farmers. In that regard, it would have been interesting to study the effect of farm size, as it has been previously shown that farm size may be related to the level of biosecurity (Delpont et al., 2020; Hernández-Jover et al., 2012; Niemi et al., 2016; Tanquilut et al., 2020a). However, such information was not available for our study.

This study optimizes the use of data collected during on-farm biosecurity inspections (DGAI, 2019). It provides a baseline assessment and compares biosecurity practices in a high number of farms, in multiple production types and in different French poultry-producing regions, differently impacted by epidemic outbreaks of HPAI. The results of this study may change the sampling criteria for future biosecurity inspection campaigns. For instance, mixed farms (producing ducks and gallinaceous poultry) and egg-layer farms, especially in the "other" region should receive special consideration. Also, data generated on high-risk farms should enable the design of more context-adapted training, diseases awareness campaigns and other types of intervention, in the view of decreasing the risk of disease incursion and spread at national level.

Ethical approval

Due to the nature of the study, formal approval from an Ethic Committee was not a requirement at the time of the study.

Data availability statement

Data that support the findings of this study are available on request from the corresponding author. Data are not publicly available due to privacy or ethical restrictions.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.prevetmed.2021.105466.

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