Murdoch University

THESIS

Economic, epidemiological, and social analyses of H7N9 influenza control strategies for yellow broilers in Guangxi, China

Hao Tang

MPA, BSc, BIT

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Thesis Declaration

I, Hao Tang, declare that:

This thesis is my account of my research and has been substantially accomplished during enrolment in this degree, except where other sources are fully acknowledged. All co-authors, where stated and certified by my Principal Supervisor or Executive Author, have agreed that the works presented in this thesis represent substantial contributions from myself. The thesis contains as its main content, work that has not previously been submitted for a degree at any other university. In the future, no part of this thesis will be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of Murdoch University and where applicable, any partner institution responsible for the joint-award of this degree.

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The research involving human data reported in this thesis was assessed and approved by Murdoch University Human Research Ethics Committee. Approval #: 2018/063.

The following approvals were obtained prior to commencing the relevant work described in this thesis: Fieldwork Safety, Risk Assessment for Murdoch Processes (RAMP).

This thesis contains published work and/or work prepared for publication, some of which has been co-authored.

Signature:

Date: 1 Oct. 2021

Abstract

The emergence of H7N9 influenza and its zoonotic transmission in China since March 2013 highlighted the continued threat from emerging avian influenza with pandemic potential. A series of policies and interventions were implemented nationwide; however, critical reviews of the effectiveness of these control strategies are lacking. This research conducted in Guangxi, a province with a significant yellow broiler industry, was designed to provide economic, epidemiological, and social evidence to inform future H7N9 control strategies in China.

A value chain study was conducted to examine the yellow broiler production and trading system in Guangxi. Stakeholders of the yellow broiler industry, their interactions, governance structure and risk practices were investigated. Yellow broiler grower companies were the dominant stakeholders. Trading platforms were key premises, linking farms and live bird markets, to be included in H7N9 influenza control programs. Poor biosecurity practices present in different premises along the value chain, pose significant challenges for the control of H7N9 influenza.

Spatio-temporal patterns of the movement of live broilers within and from Guangxi were also assessed. The most central broiler populations in the movement network were identified. The results showed that targeting areas based on movement characteristics would enable controlling H7N9 influenza more effectively compared to applying the same policy throughout Guangxi.

The yellow broiler industry stakeholders' practices, attitudes and motivations regarding H7N9 vaccination were investigated using a mixed-methods design. There was a strong willingness for the industry to continue vaccination even without government support.

The economic values of the H7N9 vaccination program were also assessed using a benefit-cost analysis. It demonstrated that the current vaccination program was economically profitable compared to not vaccinating. However, the economic returns of vaccination relied heavily on industry profits.

In summary, these research findings can help strengthen the control of H7N9 influenza in Guangxi and provide support for future avian influenza control strategies throughout China.

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Acronyms and Abbreviations

AI	Avian Influenza
AIV	Avian Influenza Virus
aOR	adjusted Odds Ratio
AUD	Austrian Dollar
BCA	Benefit Cost Analysis
BCR	Benefit Cost Ratio
CAAA	China Animal Agriculture Association
CAC	County Administrative Code
CADC (ADCC)	Centre of Animal Disease Prevention and Control
CAHEC	China Animal Health and Epidemiology Centre
CI	Confidence Interval
CNY	Chinese Yuan
CPIA	China Poultry Industry Association
DALY	Disability Adjusted Life Year
DoC	Day-old Chick
FAO	Food and Agriculture Organisation of the United Nations
FCR	Feed Conversion Ratio
FGD	Focus Group Discussion
FV	Future Value
GDP	Gross Domestic Product
GPS	Global Positioning System
HPAI	Highly Pathogenic Avian Influenza
ID	Identity Document

IQR	Interquartile Range
KAP	Knowledge, Attitudes and Practices
KII	Key Informant Interview
LBM	Live Bird Market
MARA	Ministry Of Agriculture and Rural Affairs, China
NDRC	National Development and Reform Commission, China
NHC	National Health Commission
NPV	Net Present Value
OIE	World Organisation for Animal Health
OR	Odds Ratio
PI	Prediction Interval
PV	Present Value
SCC	Strongly Connected Component
SFA	State Forestry Administration, China
SNA	Social Network Analysis
USA	United States of America
USD	United States Dollar
WCC	Weakly Connected Component
WHO	World Health Organisation of the United Nations

Authorship Declaration: Co-Authored Publications

This thesis contains work that has been published and prepared for publication.

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Co-author signatures and dates: Dr Chaojian Shen   Dr Lianbin Zou   Dr Chang Cai Prof. John Edwards   Dr Mieghan Bruce   Dr Youming Wang Prof. Ian Robertson   Dr Baoxu Huang 1 Oct. 2021

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Student signature: Date: 1 Oct. 2021
I, Mieghan Bruce certify that the student's statements regarding their contribution to each of the works listed above are correct. Principal supervisor signature: Date: 1 Oct. 2021

Chapter 1. Introduction

1.1 Background

1.1.1 H7N9 influenza and its control measures

The first human cases of H7N9 influenza were first detected in March 2013, in China (1). As of July 2021, there have been 1,568 human cases reported, including 616 deaths; with the exception of three all were in China (2). At the same time, the avian influenza A(H7N9) virus (H7N9 AIV) was also detected in poultry in China (3) and subsequently spread across the country (2). Between April 2013 and July 2021 around 2,500 virological samples from poultry and environment in live bird markets (LBMs) tested positive for the virus (2). The emergence of H7N9 influenza with pandemic potential posed a threat to human health and also caused substantial economic losses to the poultry industry in China, severely affecting the livelihoods of poultry farmers and traders (4).

The control of H7N9 AIV became a high priority for the Chinese government (5-7), which led to a systematic intervention of new policies and responses (8-11). In the initial phase of the H7N9 influenza emergency response, closure of LBMs was the primary measure to minimise the spread of disease, as visiting LBMs was identified as a critical risk factor for human infections (12, 13). At the same time, Chinese veterinary authorities attempted to improve biosecurity in LBMs in order to mitigate risks of human exposure and virus circulation among poultry being sold in the market (8). Unfortunately, these interventions targeting LBMs were not successful in halting the spread of

H7N9 AIVs to most parts of China (14, 15). The number of human infections continued to increase, rising to 791 cases between October 2016 and September 2017, exceeding the number of all cases recorded over the previous years since March 2013 (16). The virus continues to evolve; the emergence of highly pathogenic H7N9 (HP-H7N9) was reported in January 2017 which may have arisen from two different H7N9 low pathogenic viruses (17-20). The HP-H7N9 resulting in human infections and outbreaks in chickens posed an increased threat (17-20).

To tackle the growing threats to humans and poultry, the Chinese government launched a compulsory H7N9 vaccination program in poultry, first in Guangxi and Guangdong provinces in July 2017 and then implemented nationally in September 2017 (10). Since then, only four human infections have been recorded in China (21). The government surveillance results also showed that the prevalence of H7N9 AIVs in poultry remained low, with only 17 positive virological samples reported in the national surveillance program (2, 22).

The emergence of H7N9 influenza in poultry and its zoonotic transmission has highlighted the continuing threat from emerging AIVs with pandemic potential (23-27). Prior to this research, knowledge gaps that undermined the effectiveness of H7N9 influenza control in poultry had not been adequately studied. In particular, the specific characteristics of the yellow broiler industry had not been considered in the development of China’s control strategies, even though yellow broilers take up 70% of birds traded in LBMs (28, 29). Furthermore, sound multi-dimensional evidence was required as to provide "proven-to-be-effective" recommendations by policymakers (30, 31).

Questions such as - what aspects of control strategies need to be improved? how could they be improved? what social factors need to be considered in control programs? and what is the economic value of alternative control options? - need to be answered to guide the control of H7N9 influenza in poultry. Exploring these questions can also provide valuable advice on preventing the emergence of other AIVs with pandemic potential in the future.

1.1.2 Yellow broilers

The research undertaken and reported in this thesis focused on the yellow broiler industry which is the major source of live poultry trade in China, with approximately three billion birds being sold as 'live chickens' through LBMs each year, about 70% of all birds traded through LBMs (29). Given that the live poultry trade in LBMs has been identified as a critical risk factor of human infections (12, 13), it is likely that measures targeting yellow broilers would play a key role in the control and prevention of H7N9 influenza in poultry.

Yellow broilers, consisting of more than 100 breeds, are a type of Chinese indigenous chicken commonly farmed for meat production. They are often called 'yellow-feather broilers', in contrast to white broilers introduced from foreign breeds with typical white feathers (32). Yellow broilers have a different production and trading system compared with the white broiler industry (33). However, the current AI control program in China, including H7N9, does not consider the considerable differences between yellow and white broilers in terms of production and trade (28, 34). There has been no detailed investigation on the role of the yellow broiler industry in the control of H7N9 influenza.

1.1.3 Guangxi Zhuang Autonomous Region

The target study area for this research was Guangxi Zhuang Autonomous Region (hereafter referred to as Guangxi). The region covers an area of 236,700 square km, accounting for 2.5 %of China's total territory, and is the ninth-largest of China's administrative divisions (35). It is located in southern China, with neighbouring provinces Guangdong to the east, Hunan to the northeast, Guizhou to the northwest, and Yunnan to the west (Figure 1.1). Guangxi also neighbours Vietnam, with a 696 km land border with this country (35).

Figure 1.1 Location of Guangxi Zhuang Autonomous Region, China

The rationale for choosing Guangxi is two-fold. First, Guangxi is the second-largest province producing yellow broilers in China, contributing 6.7% of the annual national broiler production (36). Yellow broilers account for more than 90% of poultry production in Guangxi with the majority traded as live birds (37). Guangxi also shares live chicken trading networks with neighbouring provinces (38, 39) and Vietnam (40). Second, Guangxi has reported multiple strains of avian influenza; large numbers of human and avian H7N9 influenza cases were reported in Guangxi from 2013 to 2017, which continued (2, 41), and human infections with H5N1 and H5N6 highly pathogenic avian influenza (HPAI), were reported in 2014, 2016 and 2018 (42-44). The volume of poultry traded within the province, and neighbouring provinces and countries, coupled with the continued emergence of AIVs of pandemic potential, demonstrates the critical need for research in this context and the relevance to a wider area.

1.2 Research aim and objectives

The aim of the research reported in this thesis was to investigate and collate economic, epidemiological, and social evidence regarding the control of H7N9 influenza in yellow broilers in Guangxi. The research findings can assist in guiding the improvement of the H7N9 influenza control program in Guangxi.

This research was commissioned and supported by the China Animal Health and Epidemiology Centre (CAHEC), the national institute responsible for providing animal health policy advice and technical support to the central government. Hence, the research findings can also be used as recommendations to help policymakers to develop future AI control strategies and policies throughout China.

To achieve this aim, studies were sequentially designed and conducted with the following objectives:

1) Describe the yellow broiler production and trading system in Guangxi, including stakeholders and premises involved, their interactions and governance structure, as well as the patterns of live broiler movement;

2) Investigate the practices of yellow broiler industry stakeholders relating to H7N9 AIVs transmission and its control measures;

3) Identify critical control points and geographical areas that should be targeted to mitigate H7N9 transmission risks;

4) Assess the yellow broiler industry stakeholders' attitudes and motivations on the H7N9 vaccination program;

5) Evaluate the economic values of the H7N9 vaccination program in Guangxi, taking into account costs and benefits to both the public and private sectors.

1.3 Thesis structure

The thesis opens with a literature review (Chapter 2) relevant to the subject of this research to identify knowledge gaps. The current epidemiological understanding of H7N9 influenza and studies on economic and social dimensions of the control of H7N9 influenza were summarised. The policies and interventions to control and prevent H7N9 influenza in poultry in China were also reviewed. In this Chapter, the overview of the Chinese broiler industry was summarised through a review of government and industry reports.

The results of a value chain analysis of the yellow broiler industry in Guangxi are presented in Chapter 3. Stakeholders and premises involved in Guangxi yellow broiler production, wholesale and retail were identified. Their operations and interactions, value chain governance structure and practices relevant to the risk of H7N9 AIVs transmission were investigated and described. **(Research Objectives 1, 2 and 3)**

In Chapter 4, spatio-temporal patterns of live broilers movements from Guangxi were assessed using official movement records from 2017. The most central broiler populations in the movement network were identified to inform H7N9 influenza risk management based on the movement patterns. Additionally, the effectiveness of targeting areas based on live broiler movement characteristics was tested and compared with implementation control measures indiscriminately. **(Research Objectives 1 and 3)**

Based on the stakeholders identified as part of the research reported in Chapter 3, their practices, attitudes, and motivations regarding H7N9 vaccination in poultry were studied using a mixed-methods design in Chapter 5. The findings and their implications for the H7N9 vaccination policy were also presented. **(Research Objectives 2 and 4)**

In Chapter 6, the economic value of the H7N9 vaccination program in Guangxi compared to not vaccinating was assessed using empirical data from three consecutive years since the vaccination launched in July 2017. A benefit-cost analysis framework that accounted for both public and private sectors was used to assess economic motivations of industry stakeholders. **(Research Objectives 4 and 5)**

Finally, knowledge contributions from this research and its implications for H7N9 influenza control are discussed in Chapter 7. Limitations and future research directions are also discussed. In this final Chapter, policy recommendations are provided to policymakers in China to highlight policy implications from the research findings. Figure 1.2 presents an overview of the thesis structure and logical links between research objectives and chapters.

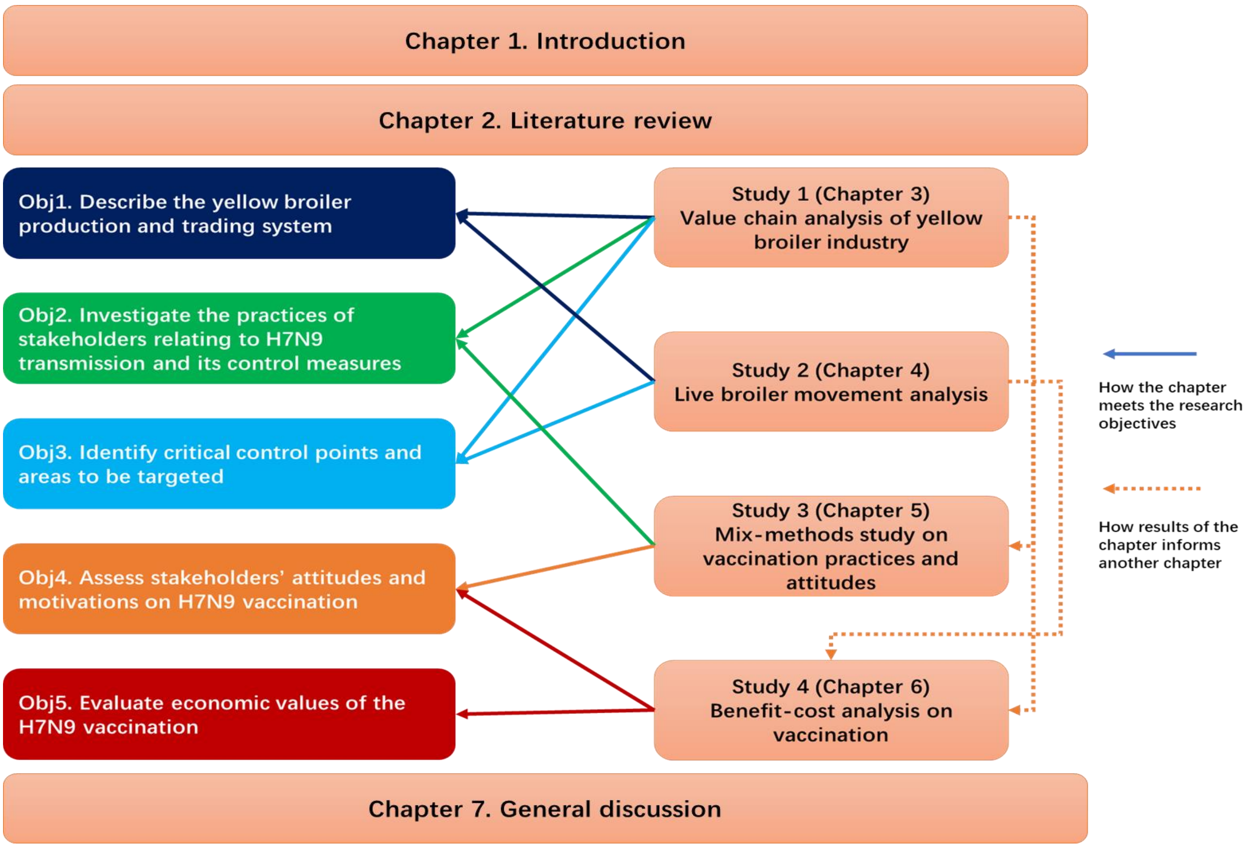

Figure 1.2 An overview of the thesis structure, illustrating how the research presented in each chapter was used to achieve the research objectives

Chapter 2. Literature Review

2.1 Introduction

In this Chapter, the current state of knowledge on the epidemiological, economic, and social factors related to H7N9 influenza and its control measures are reviewed. The Chinese policies for H7N9 influenza control and prevention from March 2013 to December 2020 are also summarised to examine existing administrative policies and associated documents. In addition, this review provides an overview of the broiler industry in China with information from government and industry reports, to outline the yellow broiler sector's position in the Chinese broiler industry. At the end of this Chapter, specific research and policy gaps are highlighted which are to be addressed in the following chapters.

2.2 Epidemiology of H7N9 influenza

H7N9 influenza was first reported in humans in March 2013 in China (1). The National Health Commission (NHC) of China confirmed three cases of human infections on 31 March 2013, including two cases from Shanghai and one from Anhui province (45). It was the first time this low pathogenic AIV had been detected in humans and caused disease. Since then, human infections of H7N9 influenza have occurred as 'waves' during the winter and spring in China, with a total of 1,568 cases reported as of 7 July 2021 (2). Among these cases, 616 deaths were reported, and the case fatality rate was 39.3% (46). Five waves of human infections were observed with the number of reported cases per wave being 134 (1^{st} wave, Feb.-Sep. 2013), 306 (2^{nd} wave, Oct.2013-Sep.2014), 219 (3rd wave, Oct. 2014-Sep.2015), 114 (4th wave, Oct. 2015-Sep. 2016), 791 (5th wave, Oct. 2016-Sep.2017). Following the 5th wave, a rapid decline in case numbers occurred, with only four cases recorded between October 2017 and June 2021 (13). A steep increase of human infections was observed in the 5th wave, with the number of cases surpassing the total case numbers of the previous four waves combined (14). Given the number of human cases and its high case fatality rate of almost 40%, H7N9 influenza has become a serious public health issue in China.

In the fifth wave of H7N9 influenza, the virus had spread to wider geographical areas covering more districts and counties, reaching 11 provinces where there were no human infections reported in the previous waves (13). A total of 30 provinces out of 31 in mainland China have reported H7N9 human infections. Hainan province was the only one with zero cases due to its geographical isolation (47). H7N9 human cases have also been detected outside of mainland China in Sabah (Malaysia), British Columbia (Canada), Hong Kong SAR, Macao SAR and Taiwan province of China. However, epidemiological investigation showed that all of these cases had been travelled in mainland China before showing avian influenza symptoms (48), which indicates a lack of autochthonous infections outside China. A previous epidemiological analysis of the data of 1,220 laboratory-confirmed human cases (as of 23 February 2017) found that most human infections were distributed in provinces near the Yangtze River delta region in East China and Guangdong province in the south (13).

The novel low pathogenic influenza A (H7N9) virus was also detected in poultry in China when human infections emerged in March 2013 (3) and since then has spread across the country(2). In the surveillance program carried out by the Chinese Ministry of Agriculture and Rural Affairs (MARA) since April 2013, approximately 2,500 virological samples from poultry population and live bird market (LBM) environments tested positive to H7N9 AIVs (2). Positive samples were detected in 30 provinces of mainland China, Hong Kong SAR and Macao SAR, where H7N9 human infections were reported (2). Positive samples were mainly from LBMs, vendors and some commercial or breeding farms. In addition to the surveillance results detected by MARA, the Food and Agriculture Organisation of the United Nations (FAO) collated data reported in 12 peer-reviewed articles and found 1,728 of 71,920 samples were virologically positive (2). H7N9 AIVs were also detected in a layer farm in Hiaure, Netherlands in June 2016 and in two broiler farms in Tennessee, USA in March 2017, respectively, but these viruses are not related to H7N9 viruses circulating in China (2, 49).

Highly pathogenic strains of H7N9 (HP-H7N9) virus have also been detected in both humans and poultry in China since January 2017, which posed an increased threat (17-20). A total of 32 human cases were observed in eight provinces of China, including 13 fatal cases (50). Of these 32 cases, 20 were from Guangdong and Guangxi provinces (50). HP-H7N9 viruses were also detected from LBMs and chicken farms in 14 Chinese provinces. A total of 66 poultry or environmental positive samples were reported as of July 2021, including 46 chickens, eight peacocks, two ducks and ten environmental samples (2).

Currently, available epidemiological and virological evidence suggests that the H7N9 AIV has limited human-to-human transmission and has not acquired the ability for sustained human-to-human spread (21). The current evidence does not demonstrate that HP-H7N9 virus is more virulent or transmissible than low-pathogenic H7N9 AIV in humans (51). The World Health Organisation of the United Nations risk assessment stated that the likelihood of sustained H7N9 virus transmission between humans remains low (21). However, given the susceptibility of a large human population due to exposure to avian sources, H7N9 remains a threat to public health.

None of China's neighbouring countries had reported the detection of influenza A (H7N9) virus in humans and poultry as of 7 July 2021 (2). According to an FAO risk assessment in July 2017, the risk of H7N9 AIVs spreading from China to its Southeast neighbouring countries (namely Vietnam, Lao PDR and Myanmar) through live poultry trade was moderate (52), because there is informal live poultry trade between China and its neighbouring countries, particularly countries in Southeast Asia region (40). Hence, FAO (52) advises that veterinary services in those neighbouring countries remain vigilant of potential risks from introduction of infected poultry or contaminated poultry products.

Despite the efforts made, control of H7N9 influenza is still challenging. Low pathogenic H7N9 infections are generally mild and asymptomatic in poultry, allowing the virus to spread silently among poultry in LBMs and farm environments without severe outbreaks detected in birds. Inapparent infections of H7N9 in poultry make it more challenging to monitor and detect viruses and thus more difficult to have effective risk communication on reducing close contact with live poultry as people cannot see the obvious signs of illness in chickens (53).

2.3 Role of live bird markets in transmission of H7N9 influenza

Exposure to live poultry is a key risk factor for H7N9 human infection. Epidemiological and virological studies have indicated that LBMs played a critical role in promoting the amplification and dissemination of AIVs therefore pose a threat to public health (54, 55). The results of an epidemiological investigation by Wang et al. (13) showed that 73% of human cases had exposure to poultry and 57% had visited LBMs. Zhou et al. (12) identified risk factors for human infections using a case-control study. The results showed that visiting LBMs was associated with an increased risk of H7N9 (adjusted odds ratio [aOR], 6.3; 95% CI, 2.6–15.3; $p<0.01$), direct contact with live poultry in LBMs (aOR, 4.1; 95% CI, 1.1–15.6; $p<0.05$), stopping at a live poultry stall when visiting LBMs (aOR, 2.7; 95% CI, 1.1–6.9; $p<0.05$), raising backyard poultry at home (aOR, 7.7; 95% CI, 2.0–30.5; $p<0.01$) and direct contact with backyard poultry (aOR, 4.9; 95% CI, 1.1–22.1; $p<0.05$). These findings are consistent with another case-control study which was conducted in April-June 2013 in eight provinces of China (47), where visiting live poultry markets had an aOR of 3.4 (95% CI, 1.8–6.7; $p<0.01$). These studies provide the evidence that LBMs are a critical control point for risk mitigation of H7N9 human infections.

Many interventions targeting LBMs in China have been implemented and the effects assessed (56-61). Market closure in some areas of China was observed to have significantly reduced the number of human infections (56, 57). For example, closure of LBMs reduced the mean daily number of infections by 99% (95% CI 93–100%) in Shanghai, 99% (92–100%) in Hangzhou, 97% (68–100%) in Huzhou, and 97% (81–100%) in Nanjing (60). Offeddu et al. (62) conducted a systematic review on the impact of LBM closure on the risk of H7N9-infection in humans. Both quantitative and qualitative data from the reviewed studies suggest that temporary closure of LBMs can reduce circulation of AIVs in the market environment and among birds in markets significantly (61, 63-65).

Closure of LBMs can affect the livelihood of many families depending upon poultry production and trade. Fournié and Pfeiffer (66) argued that the underlying epidemiological and socioeconomic system in LBMs was complicated and would trigger alternative ways of selling live poultry, for example, in underground LBMs, if demand for consumption resumed. It could increase the risk of introduction of H7N9 AIVs to other areas through the live poultry trade value chain (67). The increase in provinces and areas newly reporting human infections in the fifth wave also supports this argument (2, 67).

In addition, there was a low willingness to support permanent closure of markets in both urban and rural areas, even though the public expressed their concerns about H7N9 outbreaks, and they would visit LBMs less than usual (53, 68). This resulted in differences in the duration of market closure as well as the actual measures adopted in areas where the decision has been made by the local government (26). A clearer understanding of the specific measures and an evaluation of their effectiveness is warranted.

Pepin et al. (69) suggested that attentions should be paid to the role of upstream elements in the poultry distribution chain, not only focusing on retail LBMs. Previous studies demonstrated there were a vast number of LBMs in China (8,943 LBMs as of Feb. 2014) (70), which linked many farms with different locations across provinces through the complex trade networks (71).

In conclusion, LBMs play a critical role in H7N9 AIVs transmission in China. LBMs are an integral part of the live poultry trading network in China, and a detailed description of the whole production and trading system of live poultry sectors will provide valuable insight to inform effective control strategies. In addition, adopted practices and social acceptance of current control measures need to be further studied.

2.4 Broiler industry in China

Broiler is the term used to describe any chicken (*Gallus gallus domesticus*) that is raised for meat production. The official classification system in China categorises broilers into three major types: (i) white broiler; (ii) yellow broiler; and (iii) spent hens (32). White broilers were introduced into China from western countries in the1980s and the grandparent flocks of white broilers are originally from America and France (32). Yellow broilers are also called ‘yellow feather chicken’ or ‘colour feather chicken’ in some areas. Yellow broiler is not a specific breed of broiler chicken. It is a set of indigenous chicken breeds originating in China, including 107 breeds acknowledged by the MARA (32). In contrast to typical definitions of broilers, spent hens are included in Chinese official classification because they enter the broiler value chain and are sold in LBMs as live meat chicken. A fourth category of broilers used by the Chinese broiler industry is called “broiler-mixed”, a group of breeds that have been interbred between white or yellow broiler and layer. China is the third-largest broiler producer in the world, with a production of about 10.1 billion broilers in 2017 and about 14.69 million tons of meat (29). Chicken meat is the second highest source of animal protein for human consumption in China, accounting for 62.3% of annual poultry meat production in 2017. The poultry was second largest meat production source in China, and is less than pork (63%), and more than beef (8%) and mutton (5%), according to the official data of 2017 (36).

The scale of broiler farms in China also varies, with a very large number of small- and medium-size farms. According to the official data of 2016 (36), there were 18.7 million broiler farms that produced less than 2,000 birds per year, representing 98.46% of broiler farms in China. The farms that produced between 2,000 to 9,999 birds per year accounted for 0.92%, which is 0.17 million farms. The remaining farms, which produced more than 10,000 birds per year, comprised 0.62% of the total broiler farms nationwide (Table 2.1).

Table 2.1 Scale of broiler farms in China and Guangxi province (2016)

Source: Chinese Animal Husbandry and Veterinary Yearbook, 2017 (36)

Number of birds slaughtered per year	China		Guangxi	
	Number of farms	Share of farms (%)	Number of farms	Share of farms (%)
<1,999	18,710,173	98.463	2,837,905	98.973
2,000-9,999	175,042	0.921	23,357	0.815
10,000-29,999	61,746	0.325	4,514	0.157
30,000-49,999	27,277	0.144	1,048	0.037
50,000-99,999	18,533	0.098	321	0.011
100,000 - 499,999	7,532	0.040	145	0.005
500,000 - 999,999	997	0.005	18	0.001
>= 1 million	953	0.005	36	0.001
Total	*19,002,253*	*100*	*2,867,344*	*100*

Yellow broilers accounted for about 35% of the total number of broilers produced in China. While white broilers shared another 40%, and the rest were spent hens (layer chickens that have reached the end laying period) and white mixed broilers (interbreed between white broiler and layers) (29). Yellow broilers annual production dropped from 4.30 billion in 2012 to 3.86 billion in 2013 when H7N9 influenza emerged. Since then, it has gradually increased to 3.91 billion in 2016 but decreased again to 3.69 billion in 2017 as H7N9 human infections soared, and then increased again to 4.56 billion in 2019 (Figure 2.1) (29).

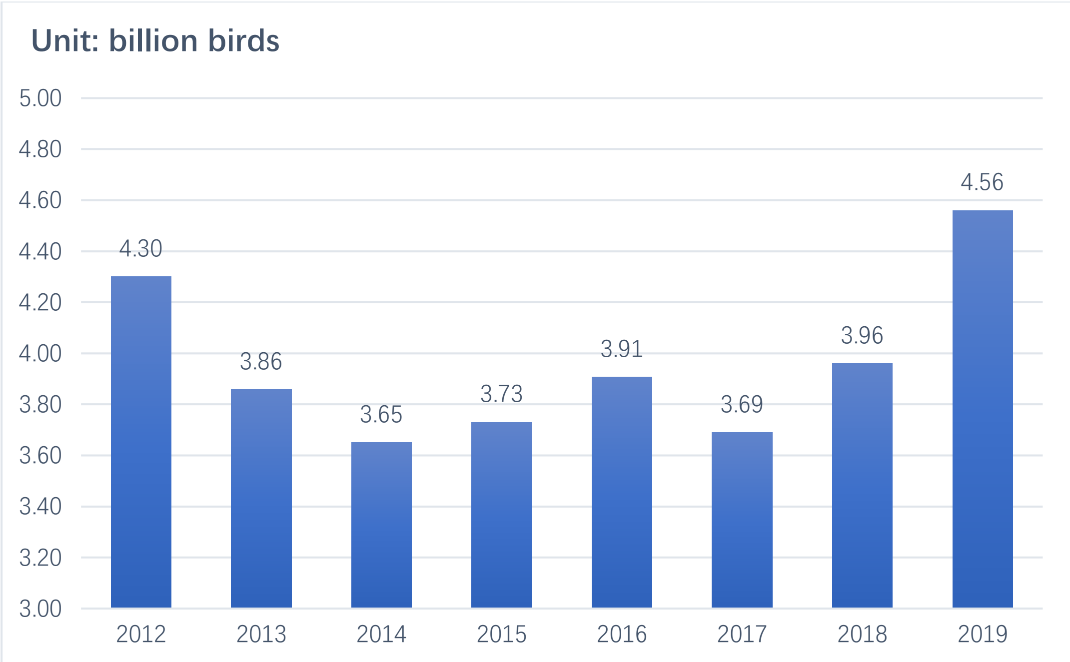

Figure 2.1 Annual production of yellow broilers in China from 2012 to 2019 (number of birds processed, in billions)

Yellow broilers have different breeds, raising periods, slaughter weights and trade channels comparing with other three types meat chickens in China (Table 2.2) (29, 72). Yellow broilers are the primary source of live poultry trade, comprising more than 70% of live poultry trade volume in China (29). Meanwhile, more than 85% of yellow broilers are traded as live birds through LBMs (33), which indicated LBMs were key premises to link a large portion of yellow broiler farms.

Table 2.2 Comparison of four types of meat chickens in China (72)

	White broiler	Yellow broiler	Broiler-mixed	Spent hens
Breeds	Export from western countries	Developed from Chinese native breeds	Mixed between white/yellow broiler and layer	Layer
Weight	2 – 2.5 kg	1.5-2 kg	1.2 -1.5 kg	Not available
Raising days	38-45 days	70 – 180 days	42-58 days	> 500 days
Trade through	Slaughter companies	Live bird markets (85%)	Slaughter companies	Live bird markets
Final product	Chilled chicken	Live chicken; Defeathered chicken	Delicatessen food; Defeathered chicken	Live chicken

There are four major production areas for yellow broilers which share more than 90% of the production volume (29, 72). Guangdong and Guangxi, are the highest yellow broiler production areas, with about 40% of production, following by Hunan and Anhui provinces (72).

There is very limited knowledge of the production and trading system of yellow broilers in China, including how yellow broilers are raised and traded, who is involved and the interactions and governance structure among different stakeholders. Due to lacking evidence, the different features of four types of meat chickens are not acknowledged in the avian influenza control policies and all meat chickens are treated as the same in official control measures regardless of their production and trading features, including H7N9 influenza (8, 28).

2.5 H7N9 influenza control policies in China

Following the emergence of zoonotic H7H9 influenza, its prevention and control became a priority for the Chinese central government. A series of policies were launched at the national level by various ministries to fulfil their responsibilities related to H7N9 influenza control and prevention. Notably, implementation of the national policies varied in different areas of China due to different levels of administration, decentralization, as well as the size and complexity of the system.

The focus of the research is on the control of H7N9 in poultry. Therefore, this review mainly focused on the policies and interventions in domesticated poultry. The policies in public health and other sectors, as well as multisectoral collaboration are also described briefly.

2.5.1 Administrative structure related to H7N9 influenza control

An understanding of the administrative structure related to H7N9 influenza control is required to contextualise the control policies. The State Council is the highest administrative organisation functioning at national level to manage and coordinate all ministries under the central government. There are two key ministries leading the control of H7N9 influenza, each of which has different responsibilities and authorisation. The National Health Commission (NHC)[1], the health authority at national level, is mainly responsible for the prevention and control of H7N9 human infections. Veterinary services and animal

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[1] NHC was formed from the National Health and Family Planning Committee (NHFPC) in 2018.

husbandry are within the Ministry of Agriculture and Rural Affairs (MARA)[2], which is the ministry responsible for H7N9 control and prevention in domesticated poultry. Other ministries involved are: (i) the State of Forestry Administration (SFA), which is responsible for control of H7N9 influenza in wildlife; (ii) the Ministry of Commerce is the highest authority for managing trade and markets; and (iii) the Ministry of Finance and the Ministry of Human Resource and Social Welfare, both of which provide administrative and financial support. The roles of the central level ministries are to provide technical supervision and guiding policies, while each ministry has its own branches at provincial and local levels to implement their policies. The branches at each level are managed by their local government (73) and follow the principle of central government policies and regulations. Local branches are authorised to make the policies adaptive to their own local contexts when necessary. The structure of veterinary services in China is shown in Figure 2.2.

The management of LBMs is also within the remit of multi-government agencies. The Institute of Animal Health Inspection, which is a local veterinary agency, is responsible for animal health inspection at wholesale LBMs, while local health authorities oversee health inspection at retail LBMs. The market management is under supervision of local branches of the Ministry of Commerce and notably they are the only enforcement force at market level. With multiple sectors involved in the development, implementation, and

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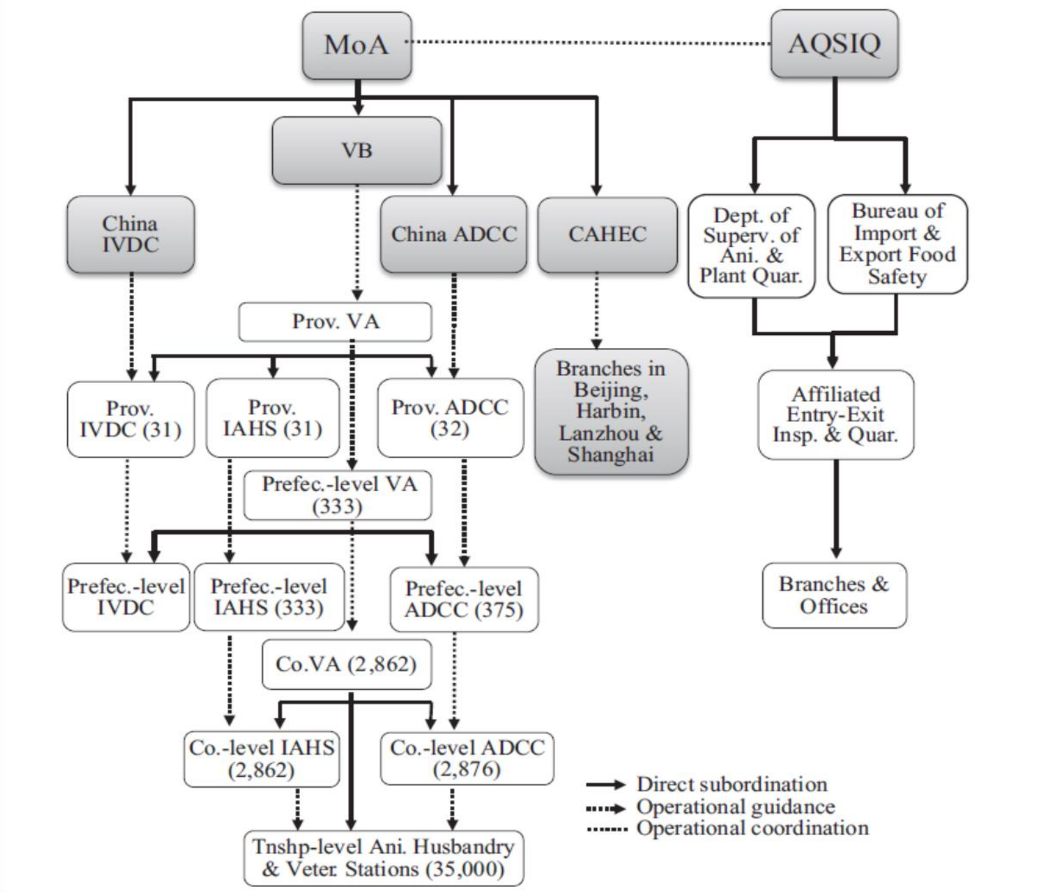
[2] MARA was formed from the Ministry of Agriculture (MoA) in 2018.

enforcement of H7N9 control policies, a detailed analysis of the yellow broiler value-chain, including governance structure, would enable more effective monitoring and evaluation.



Abbreviations: Ani.=Animal, ADCC=Animal Disease Control Center, AQSIQ=General Administration of Quality Supervision, Inspection and Quarantine, CAHEC=China Animal Health and Epidemiology Center, Co.=County, IAHS=Institute of Animal Health Supervision, Insp=Inspection, IVDC=Institute of Veterinary Drug Control, MoA=Ministry of Agriculture, Prefec.=Prefecture, Pov.=Provincial, Quar.=Quarantine, Superv.=Supervision, VA=Veterinary Authority, Tnshp=Township, VB=Veteirnary Bureau, Veter.=Veterinary

Figure 2.2 Organisational chart of public veterinary services in China (73)

2.5.2 H7N9 influenza control policies in animal health sector

The national H7N9 control policies in animal health were released by the

MARA, and some regulations were jointly made and released with other ministries. Key documents include: ‘National plan for H7N9 elimination (2014)’, ‘National plan for control and prevention of HPAI (2016-2020)’, and ‘National guideline for H7N9 influenza control and prevention (2018-2020)’. Control policies are focused on six major aspects: (i) surveillance; (ii) market closure; (iii) biosecurity; (iv) movement control of live poultry; (v) reform of the poultry industry and (vi) vaccination. Each aspect is explained in the following sessions.

2.5.2.1 Surveillance

The MARA published a nation-wide emergency surveillance plan on 7 April 2013 (28). Since then, H7N9 influenza has been included in the ministry’s national annual routine surveillance plan. Routine surveillance is carried out by the Centre of Animal Disease Prevention and Control (CADC) at each administrative level. Those centres are required to conduct random sampling on a monthly basis. There are minimum requirements for surveillance work by provincial level centres, i.e., 170 sites each province and 30 samples per site. The provincial centres are required to conduct targeted surveillance and identify the surveillance sites by themselves. The results of positive samples, both serological and virological, were to be released on the MARA official website. In response to the sudden increase in H7N9 human infections in late 2016, the MARA launched an emergency surveillance program in January 2017 to strengthen surveillance capacities in high-risk areas. Approximately 2,500 positive virological samples from poultry and LBMs environment were detected through routine and emergency surveillance programs since April

2013.

2.5.2.2 Live bird market closure

Closure of LBMs in areas where human cases and positive samples in poultry or environment were reported was recommended in a MARA announcement issued in January 2017 (34) which was then “emphasised” by the State Council on 22 February 2017 (7). Some local governments began to close LBMs as early as in 2014, following recommendations from local public health agencies. However, different areas had adopted various approaches of LBMs closures. In summary, there were three types of market closures in implementation:

i. Permanent closure: For instance, Beijing and Hangzhou

ii. Seasonal closure: For instance, Shanghai, market closed from January to April each year

iii. Temporary bans: When human cases occurred or positive samples in poultry were detected. The duration varied depending on the local government’s decision.

However, the practices of LBMs closure changed according to the disease situation, and it may have affected risk management and the control of H7N9 AIVs spread.

2.5.2.3 Improving biosecurity of live bird markets

Improvement of biosecurity management for LBMs has been addressed since January 2014 (7), and re-emphasized in MARA's documents in July 2014, November 2015 and January 2017. However, there were no specific requirements in the document before January 2017. In a document published on 23 January 2017, the MARA detailed interventions to be carried out by local veterinary authorities. This was called the '1110' policy, in which managing bodies of LBMs are required to ensure LBMs are cleaned once a day, disinfected once a week, closed for one day per month, and no birds are allowed to stay overnight in the market. The '1110' policy has also been included in several regulations after that. However, the implementation of this policy at field level and its effectiveness needs to be further assessed.

2.5.2.4 Live poultry movement management

According to the Law of the People's Republic of China on Animal Disease Prevention, animal movements within China require an animal health inspection certificate issued by the local animal health inspection agency. There are two categories for the certificate, 'A' between provinces and 'B' within provinces. In the early waves of H7N9 outbreaks, the MARA suspended live poultry movement between provinces for a short time. The health inspection of live poultry movement was highlighted in several government documents since early 2014. However, the methods of animal health inspection vary among areas and laboratory testing was not compulsory before April 2017. Additionally, symptom-based inspection is not effective for the low pathogenic H7N9 influenza. Therefore, the movement control and health inspection would have had limited effect. In April 2017, the MARA announced that laboratory-test based certificates were required for live poultry movement between provinces. With launching of poultry vaccination program, it was required that the flock antibody rate should reach 70% for the flock to be qualified for a movement certificate. Considering different capacities of local laboratories, the feasibility of this regulation needs to be reviewed.

2.5.2.5 Reform of the broiler industry

Witnessing the impacts of H7N9 influenza on the broiler industry, the Chinese government has been pushing for industry upgrading since early 2014 (7). It aimed to limit the live broiler trade and replace live broiler trade with chilled meat trade. The industry upgrading policy had four elements, encouraging 1) intensive broiler farming, 2) centralized slaughtering, 3) cold chain transportation, and 4) chilled meat trade. However, the regulatory requirements are not compulsory, and there were different responses nationwide.

2.5.2.6 Vaccination

Vaccination of domestic poultry against H7N9 AIVs pioneered in Guangdong and Guangxi in July 2017. The national roll-out began in September 2017 and was fully funded by government. To reduce cost, H7N9 vaccine has been integrated with the routine HPAI H5 vaccination program, i.e. using the H5-H7 bivalent vaccine (H5N1 Re-8 strain & H7N9 H7-Rel strain) (10). The national policy requires all chickens, ducks, geese and domestic quail, pigeons, and captive endangered bird species to be vaccinated. The recommended vaccination schedule is that poultry with a growth period over 70 days are vaccinated twice with three to four weeks intervals and those with a growth period less than 70 days are vaccinated once. Premises under zoning control or for export purposes may apply for permission not to be vaccinated for export purposes. Neither the timeline nor exit strategy was not mentioned in the document (10).

2.5.3 H7N9 influenza control policies and interventions in public health and other sectors

The National Health Commission (NHC) is the country's top health authority. On 3 April 2013, the NHC launched a national plan for the prevention and control of H7N9 human infections. The plan was updated on 10 May 2013 and 27 January 2017, respectively (9). It is the key document for health agencies to regulate all aspects of surveillance, including case detection, reporting, epidemiological investigation, sampling, surveillance, information management and risk communication. Several guidelines were also developed to provide standards on human cases diagnosis, treatment, epidemiological investigation, lab test and patient management etc.

The State Forestry Administration (SFA) is the ministry level agency in charge of wildlife conservation. It launched a surveillance plan to monitor H7N9 AIVs in the wild bird populations, which were conducted by wildlife disease monitoring stations nationwide (74).

The Ministry of Finance and the NHC jointly released a regulation to support the health insurance for H7N9 patients (75). The China Insurance Regulatory Commission also required the insurance companies to assist the agricultural department and local government for emergency response (11).

2.5.4 Multi-sectoral collaboration

A State Council meeting hosted by the Chinese Prime Minister on 10 April 2013 (6) emphasized the importance of multi-sectoral collaborations on H7N9 influenza control and prevention, followed by another two State Council meetings on 26 January 2014 and 22 February 2017 to coordinate H7N9 influenza control policies and interventions among ministries.

As a follow-up of the State Council meetings, MARA required multi-sectoral collaborations to be enhanced through the “Three work-together principle” in February 2017 (34). It means the veterinary and health agencies at different levels should all arrive at the site, carry out investigation and conduct emergency response together when human cases were detected.

2.6 Economic analysis related to H7N9 influenza

The emergence of H7N9 influenza is not only a public health problem but a serious economic issue. The China Animal Agriculture Association (CAAA) estimated that the direct economic losses to the poultry industry were more than 60 billion Chinese Yuan (10 billion USD) by the end of June 2013, and epidemics in early 2014 were attributed to further production losses estimated at 20 billion Chinese Yuan (3.4 billion USD) (4). The numbers were also quoted by the Chief Veterinary Officer of China in a media interview in 2014 (4). The broiler industry claimed these figures underestimated their real economic loss as a result of the H7N9 epidemic (33). However, both reports did not present their methodology, therefore these values are hard to verify.

The burden of human H7N9 infections was calculated by Qi et al. (76) using the data as of May 31, 2013. The total direct medical cost of H7N9 cases was 2.6 million USD. Each mild human case costs 1,619 USD, with severe cases 22,292 USD and fatal cases 32,956 USD. The total disability-adjusted life years (DALYs) was 2.77 million USD. They also estimated that the agriculture sector lost 1.24 billion USD in the ten affected provinces and 0.59 billion USD in the eight non-affected adjacent provinces. Their assessment calculated only three types of losses, namely losses from poultry slaughter, lost live poultry sales and fees for market-stall leases. Therefore, the total cost is likely to be much higher.

Several studies have pointed out that it is necessary to conduct economic analysis to guide future disease control and prevention measures, and this includes methods such as benefit-cost analysis and cost-effectiveness analysis to better understand economic returns and effectiveness of control measures (76-78). However, to the author’s knowledge, there are no published studies that thoroughly assess the economic impact or economic values of H7N9 control interventions in China.

2.7 Studies on social factors related to the control of H7N9 influenza

Several knowledge, attitudes, and practices (KAP) studies were conducted to investigate different stakeholders' risk perceptions to H7N9 in different geographic areas. Ma et al. (79) reported that 46.1% of respondents of live poultry traders in Guangzhou city recognized the risks of H7N9 infection, and 87.1% did not believe they personally face risk of getting H7N9 infection. Adoption of personal protective behaviours in relation to H7N9 infections was still low among live poultry traders and poultry farmers (79, 80), even though their knowledge of the disease and prevention measures had increased and they became more aware of their greater occupational risk compared with H5N1 influenza. It is evident that knowledge is not a barrier to reducing transmission risk and therefore the disparity between knowledge and practice requires further investigation.

Previous studies have indicated that consumption behaviours may be influenced by disease emergencies. A study in Zhejiang province found 75% of the general public had basic knowledge of H7N9 and about half of the respondents voiced concerns about being affected with H7N9. (81). Goodwin and Sun (82) examined public threat perceptions on H7N9 in the early stages. A total of 1,011 people from Shanghai city were interviewed in April 2013, two weeks after the first human case reported. It found that the level of anxiety was moderate and the levels of trust in Chinese government advice about H7N9 was high at that stage. The results also indicated the avoidance of buying poultry or eggs was the most frequent response among the respondents.

Little information has been reported on how the stakeholders responded to the control measures that were implemented. The attitudes and acceptance of central slaughtering were assessed in different stakeholder groups in

Guangdong (83). The acceptability by live poultry traders was only 37.9%, lower than by consumers (57.1%) and poultry farmers (62.6%). A previous study in Guangzhou, the capital city of Guangdong, showed even lower acceptability by live poultry traders of central slaughtering (79). However, central slaughtering is part of the control measures targeted to the live broiler trade and may be affected by other interventions. Therefore, stakeholders' attitudes to control interventions need to be examined as a whole.

The cross-sectional KAP study could only provide descriptive data on live poultry exposure, risk perception, and behaviours. It was not able to identify changes over time in risk perception or preventive behaviours. In addition, it requires qualitative research to explore the reasons for the stakeholders' adapted behaviours, their attitudes towards government-promoted interventions and the impact of these attitudes have on the effectiveness of control interventions.

2.8 Conclusions

The literature reviewed here demonstrates there are still challenges in H7N9 influenza control and prevention even though scientists have made significant progress in understanding the viruses (17, 22, 84). Evidence shows effective control of many zoonotic diseases is challenging because intervention efforts are affected by epidemiological, social, and economic factors, including the dynamics of livestock value chains, stakeholders' risk perceptions and economic incentives (85-91). It is the same for H7N9 influenza (92, 93). However, there are few studies exploring dimensions of these factors and their interrelations regarding H7N9 influenza control in China. Three significant gaps have been identified by reviewing the existing literature.

Firstly, the yellow broiler production and trade systems are not well described, even though they comprise more than 70% of live poultry trade through LBMs in China (29). The characteristics of the yellow broiler industry had not been considered in the current H7N9 control programs while several studies indicate that understanding of livestock systems is crucial for animal disease control and effective risk management (94-97). Thus, it is unrealistic to have an effectively targeted control of H7N9 influenza without a holistic picture of the yellow broiler industry.

Secondly, existing studies on stakeholders' social attitudes towards H7N9 influenza are not sufficient for good evidence-based policymaking. Research has been focused on stakeholders' acceptance of control measures, i.e., closure of LBMs and reducing live bird trade (98-100). There is no research attitudes towards vaccination in poultry, even though it is considered one of the most important control measures for H7N9 influenza. It is necessary to have up-to-date knowledge on the stakeholders' attitudes and practices in response to the current H5-H7compulsory vaccination policy. It is also meaningful to consider their suggestions for improvement of vaccination policy.

Thirdly, the economic return of H7N9 vaccination program has not been examined while significant public funding was spent in this control measure. It is believed that H7N9 avian influenza had significant economic impacts, both on human health and the poultry industry (42, 76, 101), yet the available data in this regard are too general and fragmented for a complete picture of economic losses (4, 76). It is therefore not possible to provide solid economic evidence to inform policymaking.

In conclusion, the lack of evidence for the above-mentioned aspects impedes the policy intention of improving H7N9 influenza control strategies. My study aims to fill in some crucial knowledge gaps within these three dimensions, and to contribute to policy changes for better control of H7N9 influenza and other emerging zoonotic avian influenza.

Chapter 3. Value Chain Analysis of Yellow Broiler Industry in Guangxi, China to Inform H7N9 Influenza Control Strategies

Preface

Effective control of animal disease requires a sound understanding of the relevant livestock production and trade systems implemented (94, 102-104). However, there has been limited research on how the yellow broiler industry works in China and its role in transmission of H7N9 AIVs. This is despite the fact that yellow broilers comprise approximately 70% of poultry trade through LBMs (33) which is the main site where H7N9 zoonotic transmission occurs (12, 60). Currently, the yellow broiler production and trading system's characteristics are not recognised in the prevention, control and risk management of H7N9 influenza in China (8, 105). The current control program is designed for all types of chickens and does not consider the different risk levels associated with different types of chickens, which can hamper the effectiveness of control measures.

In this chapter, a detailed description of the yellow broiler production and trading system in Guangxi are presented by conducting a value chain analysis. Stakeholders involved in yellow broiler production and trading and how they operate and interact within the system were identified and described. The findings help identify the risk populations, risk pathways and stakeholder engagement, which can subsequently be used to improve H7N9 influenza risk management by policymakers in China.

The text of this chapter is identical to that in the manuscript published in '***Preventive Veterinary Medicine***' with minor amendments. Supplementary materials are presented in Appendix A of this thesis.

This chapter can be found published as:

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The research included in this chapter was presented as poster at ***The 15th International Symposium of Veterinary Epidemiology and Economics (ISVEE 15), 12 - 16 November 2018, Chiang Mai, Thailand.*** and was awarded the best poster presentation of the conference

Abstract

Yellow broilers are the primary source of poultry consumption in China and the predominant trade of live poultry. However, knowledge of the value chain is limited, which is vital evidence for the effective control of H7N9 and other zoonotic avian influenza. The aim of the study was to map the yellow broiler value chain in Guangxi Zhuang Autonomous Region, China and investigate its governance structure and practices relevant to the risk of H7N9 transmission.

A value chain analysis was conducted in five areas of Guangxi from May to August 2018. To map the value chain, three focus group discussions (FGDs) were conducted, which enabled the stakeholders, products and premises involved and their interactions to be identified. Then, 55 key informant interviews (KIIs) collected qualitative data on stakeholders' profiles, practices, and interactions with other stakeholders, as well as rules/norms that exist along the value chain. On-site observations were also carried out at premises of different types, along the value chain to complement and validate findings of KIIs and FGDs. Participants were also asked to provide proportional estimates of each component in the value chain where possible. The qualitative data from FGDs, KIIs and on-site observations were analysed to create stakeholder profiles and a diagram of product flows and stakeholders' interactions. Thematic analysis was used to identify the governance structure of the value chains and practices relevant to the risk of H7N9 transmission.

The stakeholders and premises involved in Guangxi yellow broiler production, wholesale and retail were described, as well as their interactions. Contract

farming is extensively adopted in Guangxi; consequently, yellow broiler grower companies are the dominant stakeholders. The trading platform was identified as a key premise linking farms and live bird markets. The thematic analysis highlighted poor biosecurity practices in different premises along the value chain, which was supported by on-site observations. The operation of trading platforms reported in this study presents a disease risk but is not considered in the current H7N9 control programs. The study suggested that biosecurity management gaps need to be addressed through government-industry partnerships that require engagement with private stakeholders in the planning and implementation of H7N9 control strategies incentivising participation of grower companies, wholesalers, and retailers.

3.1 Introduction

Avian influenza A(H7N9) caused 1,568 human cases with 40% case fatality rate and has spread widely in China's poultry population since it was first detected in humans in March 2013 (1, 2). The H7N9 emergency posed a threat to human health with pandemic potential and caused substantial economic losses in China (4). Exposure to live chickens is a significant risk factor for H7N9 infection in people (12). Epidemiological and virological studies have indicated that live bird markets (LBMs) play a significant role in promoting the amplification and dissemination of avian influenza viruses which pose a threat to public health (54, 55). Previous studies also found that LBMs had significant roles in transmitting H7N9 infection to humans in China and contained critical control points for risk mitigation (12, 13). However, LBMs were only one part of the complex live poultry trade networks (67, 71). Several studies have indicated that understanding the livestock system is crucial for zoonotic disease control and effective risk management (94-97). Therefore, some scientists argue that it is necessary to pay attention to the role of upstream elements of the live poultry value chain for effective control of H7N9 influenza and other emerging zoonotic avian influenza (26, 66). The Food and Agricultural Organisation (FAO) and World Organisation for Animal Health (OIE) also suggested focusing on the “contain at source” principle with the improvement of farm management and biosecurity along the market chain (106).

The primary source of the live poultry trade in China is yellow broilers, and about three billion of these are sold as ‘live chickens’ through LBMs each year

(29). Yellow broilers are a type of Chinese indigenous chickens with more than 100 breeds used for meat production (32). They are often called 'yellow-feather broilers', in contrast to white broilers introduced from foreign breeds and typically had white feathers (32, 107). The yellow broiler industry comprises almost 40% of total meat chicken production in China (29). It has different production and trading systems compared with the white broiler industry (29, 33). However, all types of chickens used for meat production are considered the same in the current policies for avian influenza control in China, including for H7N9 influenza (5, 8, 28). In this context, the yellow broiler production and trading system's characteristics were not recognised for their role in the control and risk management for H7N9.

Guangxi Zhuang Autonomous Region (hereinafter referred to as Guangxi) is the second-largest yellow broiler production province in China, contributing to about 6.7% of the annual national broiler production in 2017 (36). It also faces severe challenges in controlling H7N9 and other avian influenza. Both human and avian H7N9 cases were reported in Guangxi as well as human infections with H5N1 and H5N6 highly pathogenic avian influenza from 2013 to 2017 (2, 42, 43). Considering that more than 90% of broilers produced in Guangxi were yellow broilers, most of them were traded through LBMs (37). Therefore, it is impossible to effectively control H7N9 influenza in Guangxi without a complete understanding of the yellow broiler production and trading system.

Value chain analysis is a systematic approach for understanding livestock production and trading systems to provide evidence for disease risk analysis and management (108). It provides a practical framework to analyse the functioning of the chains that link production systems, trading sites, and consumers, with particular attention to the stakeholders' interactions, practices, and motivations (108, 109). Value chain analyses of poultry systems that identify implications to avian influenza control have been conducted in many areas of the world and provided essential knowledge for the understanding of the epidemiological and social aspects of avian influenza transmission (94, 96, 103, 110, 111). However, to the authors' knowledge, published studies documenting the yellow broiler value chain in China are lacking. Therefore, very little is known about how yellow broilers are produced and traded, who was involved and the governance structure among them. Such information is vital for the development of more effective H7N9 control strategies, which are tailored to the characteristics of the industry.

This study aimed to a) map the value chain of yellow broiler production and trading system in Guangxi, including stakeholders, their operations and interactions; b) investigate the governance structure by identifying key stakeholders and rules that could be of importance for planning the H7N9 control strategies; c) identify practices relevant to the risk of H7N9 transmission along the value chain.

3.2 Methods and Materials

3.2.1 General overview

A cross-sectional study on Guangxi yellow broiler value chain was conducted from May to August 2018. Firstly, a map of the value chain was developed, identifying people, products and premises involved in the yellow broiler production and trading and providing a description of their characterisation, flows and interactions as well as the behavioural practices along the chain (108, 109). Then, the value chain's governance structure was investigated to focus on who and what factors govern these chains, what rules/regulations, and incentives and sanctions influence stakeholders' practices. Lastly, the study focused on identifying critical control points and practices present in the chains that could affect the risk of H7N9 influenza transmission.

3.2.2 Study area

The study was carried out in three counties, Xingye, Rong and Wuming, and two cities, Nanning and Yulin, of Guangxi (Figure 3.1). After consultation with the provincial veterinary authority, these areas were purposively selected, the Guangxi Centre of Animal Disease Prevention and Control (CADC). Xingye, Rong and Wuming are areas with a large number of yellow broiler growers and a diverse range of farm structure and operations (112). Moreover, as these counties successfully developed their yellow broiler industry in the late 1990s, their structure and approach have been followed by many other areas in Guangxi interested in developing their yellow broiler grower sector. Nanning (human population = 3.97 million) and Yulin (human population = 2.94 million) were selected because of they are two urban areas near the three counties (Figure 3.1) which have different types of live bird markets and close trade relationships with the yellow broiler grower areas, including the three study counties (113).

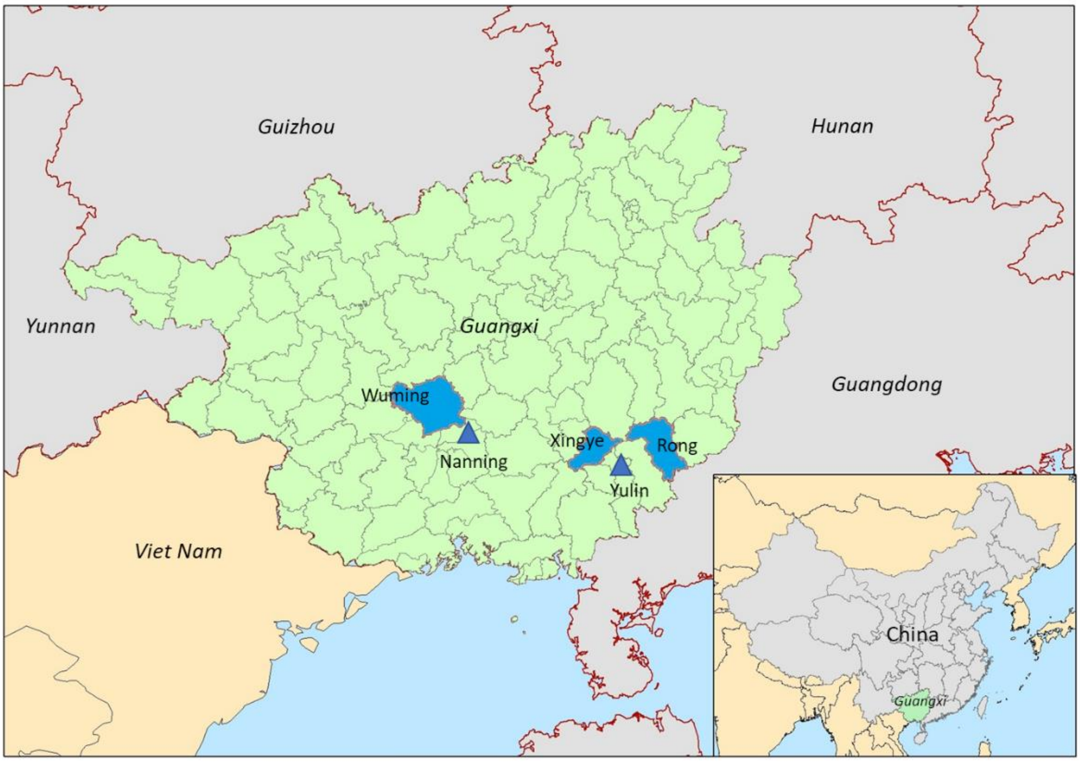


Figure 3.1 Location of Guangxi Zhuang Autonomous Region of China and surveyed areas (three counties in blue: Wuming, Rong, and Xingye; two cities in the blue triangle: Nanning and Yulin)

3.2.3 Data collection

Focus group discussions (FGDs), key informant interviews (KIIs) and on-site observations were conducted in the study areas to collect data. FGDs focused on mapping the value chain, including identifying stakeholders, products and premises involved and describing their profile, flows and interactions. While KIIs collected qualitative data on stakeholders' profile, practices and interactions with other stakeholders and rules/norms that exist along the value chain. On-site observations were performed at different types of premises along the value chain to complement and validate findings of KIIs and FGDs.

Participants were also asked to provide proportional estimates of each component in the value chain and business volume, where possible. The data collection process is presented in Figure 3.2.

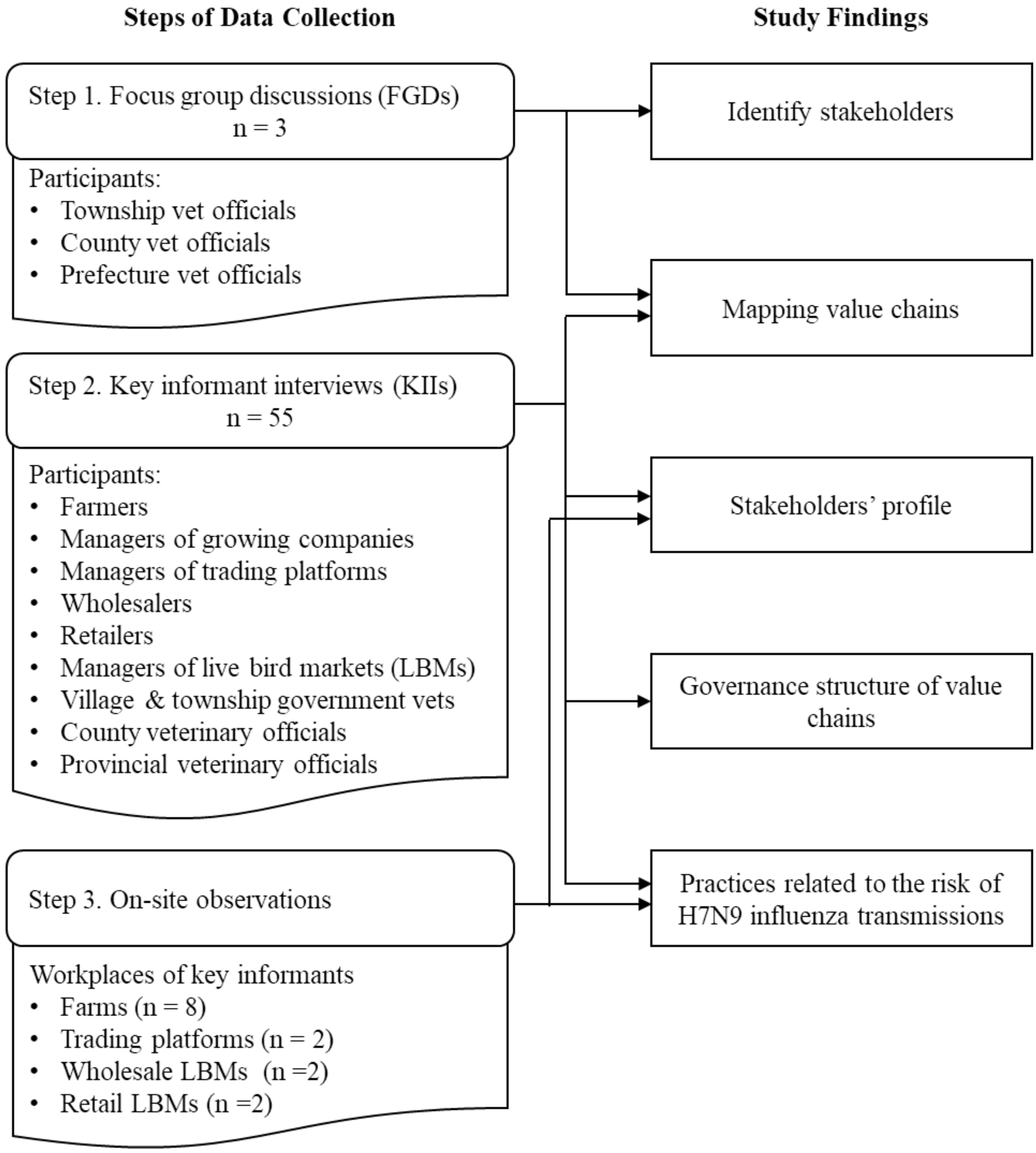


Figure 3.2 Data collection steps used in the study and each step's contributions to the study findings

Firstly, a FGD workshop was held in each county, gathering veterinary officials from the prefecture (superior level of the county), county, and township (the level below county). The participants were purposively selected, based on discussion with provincial CADC officials, to ensure participants had significant experiences working with the yellow broiler industry. They were invited by phone calls by author LBZ, and their participation was voluntary. Each workshop ran for about 60 to 90 minutes in Chinese and was facilitated by authors HT, CJS and LBZ. Oral consent was obtained from each participant at the beginning of the workshop then recorded in a list, after a brief introduction of the study and explicit explanation of the participant's rights. The participants were asked to identify the stakeholders involved in the local yellow broiler value chain and explain their profile first and draw a flowchart of value chains that focused on the flow of products and interactions among stakeholders. They were also asked to provide numbers of each stakeholder, production volumes and proportional estimates of each component in the value chain where possible. Participants at lower administrative or less senior positions were invited to speak first in FGDs, and they were encouraged to express their thoughts during the discussion to allow an open discussion without considering their administrative levels. After receiving participants' approval, notes of discussion were taken by a rapporteur instead of audio recording. HT and LBZ checked notes for any information missed, then created the word document for the notes of each FGD.

Subsequently, KIIs were conducted individually at the participants' workplace by HT, CJS and LBZ. Key informants were nominated during the FGDs, then invited through phone calls by LBZ to obtain their agreement on voluntary participation. Each stakeholder identified from the value chain mapping was included in the nominations. The semi-structured interview approach was employed using open-ended questions (Appendix A.1) to collect precise information on stakeholders' profiles and business practices, interactions among stakeholders and rules/norms that exist in their business practices and interactions with others. The questions were piloted with three participants and were adjusted to minimise inappropriate interpretation. In addition, interviewees were asked to verify and complement the value chain's flowchart, which the FGD participants had developed. An amendment would be made when at least two interviewees suggested corrections or additions.

Each interview took 40 to 60 minutes and was conducted in Chinese to allow interviewees to elaborate on their views without language constraints. Oral consent was obtained with each participant before the interview started, and was recorded in a list. As most interviewees did not provide consent for audio recording, notes were taken by two people, a note-taker and an interviewer, then compared and integrated afterwards. When discrepancies occurred between the recorded notes, HT or LBZ checked with the interviewees by phone.

Lastly, HT, LBZ and CJS also observed the infrastructure, facilities, routine operations and biosecurity practices at the stakeholders' workplace using the checklist (Appendix A.2) after the interview. The workplaces included different types of yellow broiler farms, trading platforms, wholesale and retail LBMs. The observations at each location were recorded in notes, photos and video clips, and were used to validate and complement the information that interviewees provided.

3.2.4 Data analysis

Firstly, the value chain mapping involved creating stakeholder profiles and a diagram of product flows and stakeholders' interactions. To create the stakeholder profile, the relevant data from FGDs, KIIs and on-site observations were grouped according to identified stakeholders to structure the qualitative information gathered. Then data of each stakeholder were coded into 1) definition, 2) business model, 3) operation, 4) type/source of inputs, 5) type/source of outputs, and 6) infrastructure/facilities, then were analysed to create the narrative of each stakeholder profile. A flow diagram to show product flows and interaction among stakeholders was developed by combining the different flowcharts obtained in each FGD and amendments from key informant interviews. Proportions estimated by participants were indicated in the diagram where available. Two reports, "White paper of yellow broilers industry in China" (72) and "Survey on yellow broiler production in Guangxi" (112), were used to triangulate the information obtained from the study. When data and information inconsistencies or gaps were detected, further data collection from key informants was carried out, and the profiles and maps were updated. The final proportion reported was taken from the source deemed most reliable.

Subsequently, thematic analysis (114, 115) was used to identify the value chains' governance structure and potential risk practices relevant to H7N9 influenza transmission associated with each profile. Firstly, key categories of the governance structure and potential risk practices were identified based on the research focus. Analysis of governance structure focused on 1) dominant stakeholders who were influential to resource allocation, product price and trade pathways, 2) rules and regulations in the value chain and 3) incentives and sanctions influencing stakeholders' practices (109). Potential risk practices included: 1) biosecurity management; 2) production operation; 3) trading operation; and 4) slaughter and disposal (108). The qualitative data from the FGDs, KIIs and on-site observations were coded to identify themes or practices for each category. The identified themes were used to structure the narrative of this analysis. Findings of potential risk practices were grouped into three structural components identified from the value chain mapping, i.e. farm, trading platform and live bird markets.

HT and CJS independently coded the notes, and then coding was compared to ensure the coding process's reliability. Both authors examined the themes for overlap and redundancy. The software QSR NVivo 12 Pro was used to conduct qualitative data analysis and synthesis. Data were analysed on original notes written in Chinese; the results were then translated into English by HT and checked verbatim by another bilingual author CC. When translation discrepancies occurred, two authors discussed together to identify more accurate translations.

3.3 Results

The overall description of yellow broiler production in three counties was summarised from the FGDs (Table 3.1). A total of 23 veterinary officials attended three FGDs (n = 6,8 and 9), and 55 stakeholders from different components of the value chain were interviewed individually. Participants' socio-demographic information is presented in Table 3.2. On-site observations were conducted in eight farms, two trading platforms, two wholesale LBMs, and two retail LBMs; each site's operational status was shown in Table 3.3.

Table 3.1 Overall description of yellow broiler production of Xingye, Wuming and Rong of Guangxi, China (2017). Figures were summarised from focus group discussions (FGDs)

	Xingye	Wuming	Rong
Annual production	85 million chickens	43 million chickens	9 million chickens
Proportion of total annual production of Guangxi	12%	6%	1%
Number of yellow broiler farms	3,500	927	486
Number of people working in the yellow broiler production and related fields (approx.)	15,000	2,100	3,500
Number of yellow broiler grower companies	15	4	8
Number of local veterinary staff	214 village para vets 48 township-level officials	271 village para vets 87 township-level officials	266 village para vets 71 township-level officials

Table 3.2 Socio-demographic information of the participants of focus group discussions (n= 23) and key informant interviews (n = 55) in Guangxi, China 2017

Type of Institutes (number of institutes)	Role of participants in the institute	Number of participants	Gender of participants (Male=M, Female = F)
Focus Group Discussions (FGDs) (n= 23)			
Prefecture veterinary agency (2)	Veterinary officials	7	5M, 2F
County-level veterinary agency (3)	Veteirnary officials	7	4M, 3F
Township-level veterinary agency (9)	Veteirnary officials	9	9M
Key Information Interviews (KIIs) (n=55)			
Farm (8)	Farmers - Contract farmers - Independent farmers - Work in company-owned farm	9 - 5 - 2 - 2	7M, 2F
Yellow broiler grower company (9)	Managers Technical staff	9 6	9 M 6 M
Selling platform (2)	Managers	4	4 M
Wholesale Live Bird Markets (LBMs) (2)	Wholesalers Market managers	7 2	2M, 5F 2M
Retail LBMs (2)	Retailers Market managers	2 2	2F 2M
Village and township level veterinary agency (6)	Village para vets Township official vets	6 3	5M, 1F 1M, 2F
County-level veterinary agency (3)	Veterinary officials	3	2M, 1F
Provincial veterinary agency (1)	Veterinary officials	2	2M

Table 3.3 Operational status of observation sites in Guangxi, China

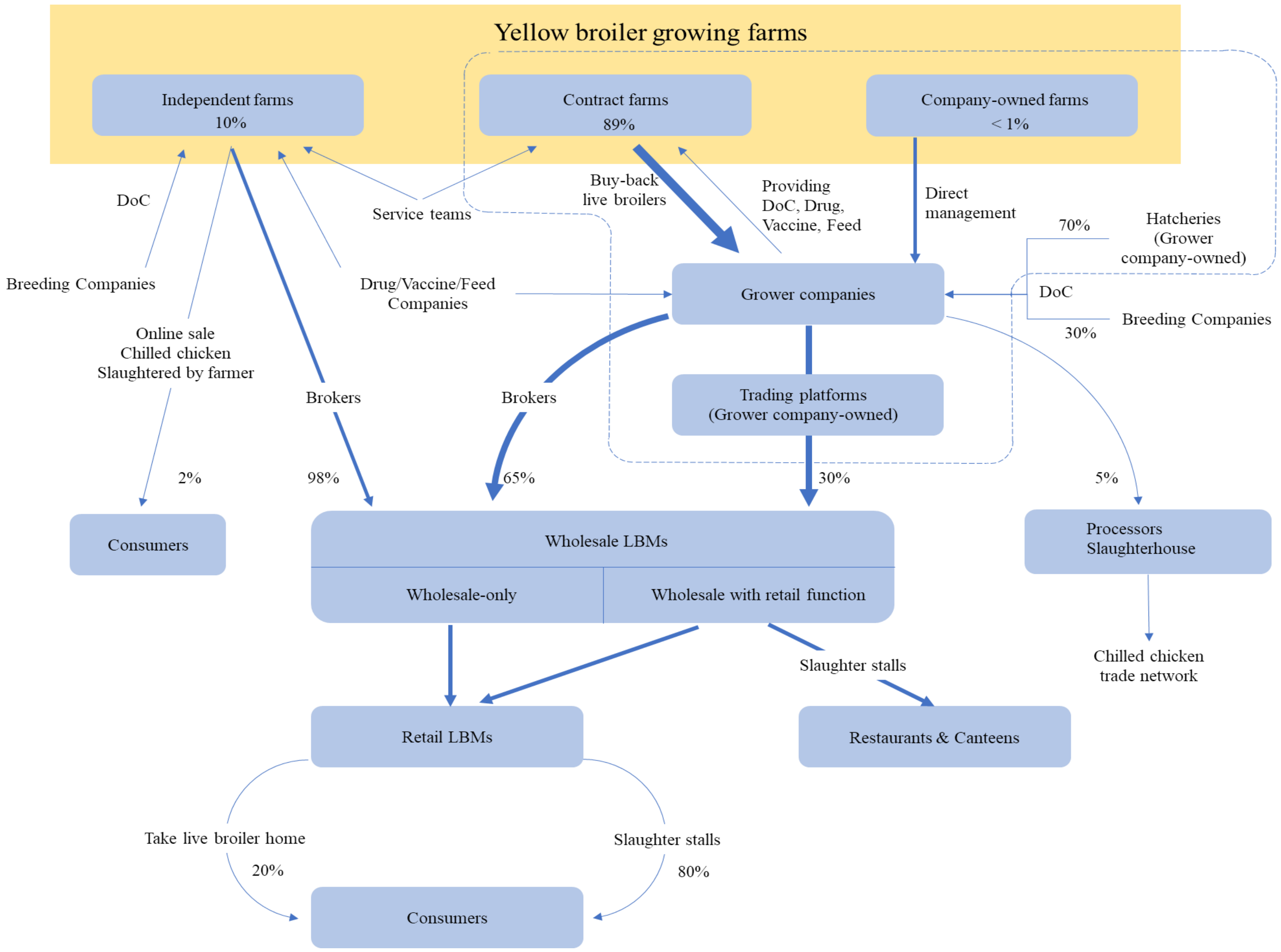
Type of Institutes (number of institutes)	Location of observation sites	Operation status of site (2017)
Farms (n=8)	Contract farm A, Xingye	- Number of broilers per batch: 7,000 - Breed group: mid-speed* - Year of operation: 14
	Contract farm B, Xingye	- Number of broilers per batch: 5,000 - Breed group: slow-speed* - Year of operation: 5
	Contract farm C, Wuming	- Number of broilers per batch: 8,000 - Breed group: fast-speed* - Year of operation: 8
	Contract farm D, Wuming	- Number of broilers per batch: 12,000 - Breed group: mid-speed* - Year of operation:10
	Contract farm E, Rong	- Number of broilers per batch: 10,000 - Breed group: fast-speed* - Year of operation: 8
	Independent farm A, Xingye	- Number of broilers per batch: 15,000 - Breed group: slow-speed* - Year of operation: 20
	Independent farm B, Wuming	- Number of broilers per batch: 8,000 - Breed group: slow-speed* - Year of operation: 15
	Company-own farm A, Rong	- Number of broilers per batch: 80,000 - Breed group: mid-speed* - Year of operation: 3
Trading platform (n=2)	Platform A, Xingye	- Daily trade volume: 60,000 -70,000 - Number of farms managed by the company: 1,200 - Staff: 40
	Platform B, Wuming	- Daily trade volume: 30,000 -50,000 - Number of farms managed by the company: 688 - Staff: 22

Type of Institutes (number of institutes)	Location of observation sites	Operation status of site (2017)
Wholesale Live Bird Markets (LBMs) (2)	Wholesale LBM A, Nanning	- Daily trade volume (avg.): 120,000 - Number of stalls: 171 - Slaughter stalls: 19
	Wholesale LBM B, Yulin	- Daily trade volume (avg.): 30,000 - Number of stalls: 80 - Slaughter stalls: 5
Retail LBMs (2)	Retail LBM A, Nanning	- Daily trade volume (avg.): 600 - Number of stalls: 21
	Retail LBM B, Yulin	- Daily trade volume: 200 - Number of stalls: 6

* Breed group: fast-speed: slaughter age 60-80 days; mid-speed: slaughter age 81-110 days, slow-speed: slaughter age >110 days

3.3.1 Yellow broiler value chain mapping

The structural components and interactions among the yellow broiler value chain stakeholders are briefly presented in Figure 3.3.



Yellow broiler growing farms
Independent farms
10%
Contract farms
89%
Company-owned farms
< 1%
DoC
Breeding Companies
Service teams
Buy-back
live broilers
Providing
DoC, Drug,
Vaccine, Feed
Direct
management
70%
Hatcheries
(Grower
company-owned)
DoC
Breeding Companies
30%
Drug/Vaccine/Feed
Companies
Grower companies
Online sale
Chilled chicken
Slaughtered by farmer
Brokers
Brokers
Trading platforms
(Grower company-owned)
2%
98%
65%
30%
5%
Consumers
Wholesale LBMs
Wholesale-only
Wholesale with retail function
Processors
Slaughterhouse
Slaughter stalls
Chilled chicken
trade network
Retail LBMs
Restaurants & Canteens
Take live broiler home
20%
Slaughter stalls
80%
Consumers

Figure 3.3 Flow chart of the yellow broiler growing and trading value chains in Guangxi, according to focus group discussions and individual key informant interviews. The percentages indicate the volume of products (as a proportion of the total volume handled by the stakeholder at the origin of the arrow) moving through each component (except for the % of farms at the top of the diagram). Dotted line indicates the premises managed by grower companies

* DoC: Day-old-chicks; LBM: Live bird market

3.3.1.1 Structural components and their functions

3.3.1.1.1 Yellow broiler farms

According to the operation mode, three types of yellow broiler farms were identified in the study areas; 89% were estimated to be contract farms, 1% company-owned farms, and 10% independent farms. Interviewees pointed out that few backyard farmers with a small number of broilers were raised but only for the farmers' own consumptions. Contract farms were operated based on a partnership between farmers and yellow broiler grower companies. Farmers own the contract farm and operate it by following the company's instructions. They were also responsible for providing production infrastructure and facilities, including sheds and feeding and watering appliances. The yellow broiler grower companies were responsible for the supply of day-old chicks, feed, vaccines and pharmaceuticals to farmers, as well as providing production guidance and veterinary services. The company guarantee to buy back all the chickens if they meet the quality requirements.

In contrast, company-owned farms were entirely operated by companies with a standard management system, and they were typically intensive farms with a large production capacity. The remaining 10% of grower farms were independent, run by independent farmers. Interviewees reported that the independent farmers were most likely to be more experienced in yellow broiler production than farmers operating contract farms.

Yellow broiler chickens typically lived on the ground with permanent access to water and feed, and they were kept in shelters with a density of 10 to 15 birds per square meter at the growth stage. It was reported that the slaughter ages of yellow broilers ranged from 60 to 150 days when the weights reached 1.5 to 2.0 kg. For trading and management purposes, the industry grouped the more than 100 yellow broiler breeds into three categories according to the slaughter ages, i.e. fast-speed (60-80 days), mid-speed (81-110 days) and slow-speed (>110 days). About 80% of yellow broilers were raised for more than 80 days.

Participants estimated that about 75% to 80% of yellow broiler farms grew 7,000 to 10,000 chickens per batch in the study areas. Farms growing 10,000 to 20,000 birds per batch accounted for 10% to 15%, and the remaining 10% of farms produced 5,000 to 7,000 birds per batch. Less than 0.1% of farms were intensive farms that produced 80,000 to 200,000 chickens per batch, and they are all company-owned farms. Interviewees explained that farms with size below 5,000 chickens found it was difficult to make enough profit to survive as the unit profit margins of yellow broiler production were relatively low in Guangxi. Participants also reported that a typical shed size in a yellow broiler farm ranged from 2,000 to 5,000 chickens, and sheds holding over 5,000 chickens were rarely seen in the study areas as it would be challenging to have enough ventilation in the hot and humid summer.

Facilities varied among farms, and most contract and independent farms were only equipped with simple facilities. About 90% of the farms used half-open sheds, with low walls without windows built by wood, brick and steel materials. Many of these farms used natural ventilation or pedestal fans. In contrast, about 10% of farms use closed sheds that are newly built and equipped with ventilation, cooling pads, auto feeding and watering systems. Those farms were mainly company-owned farms with a few contract farms. It was rare for independent farms as it requires a substantial investment from growers. Interviewees pointed out such farms often used for raising yellow broilers where the slaughter-age is below 80 days as this type of yellow broilers does not require outdoor exercise.

3.3.1.1.2 Grower companies

Most yellow broiler grower companies were private, and these managed about 90% of yellow broiler farms in the study areas, including contract farms and company-owned farms. It was reported that the number of contract farms that each company managed varied ranged from about 100 to 2,000 farms. Interviewees also estimated that about 70% of grower companies had sub-branches in other areas or were a subsidiary belonging to a large corporate group. In comparison, around 30% of grower companies only operated locally, and most of them hold a smaller number of contract farms, usually less than 200 farms. Interviewees pointed out that the companies had a small number of contract farms usually targeted different market demands by providing local special breeds to minimise the competition with large companies. The companies had a large number of contract farms that were often involved in interprovincial trade, which supply their broilers to more expansive areas.

Participants mentioned that the grower companies recruited full-time technical staff who helped with contract farms' daily operation, including arranging production schedules, monitoring farmers’ operation, and referring problems to the veterinarians. Technical staff supported 20 to 70 farms depending on the geographical distribution of the farms they served and made regular visits to farms as required, at least once a week.

3.3.1.1.3 Service company

Service companies were private self-organised groups that all provided a full range of labour services, including vaccination, beak trimming, applying leg tags and loading chickens for sale for both contract farms and independent farms upon the requests. A service company usually covered several villages or townships which were close to each other. Interviewees reported that about half of all farmers used the service company regularly as convenient, efficient and affordable.

3.3.1.1.4 Trading platform

A trading platform (hereinafter referred to as the platform) is a facility built by the yellow broiler grower company to assemble the broilers from the contract farms and company-owned farms before sending them to the wholesalers. Participants pointed out that the platform would provide more varieties to wholesalers and save their time than picking up broilers from the farms and making it easier for the company to manage the sales. Interviewees reported that each platform was operated by one yellow broiler grower company only, and it did not accept chickens from other companies' farms.

The platform operations were described by interviewees and observed by the researchers. The broilers were packaged into the company's cages at the farm and then transported by the company's trucks to the platform in the early morning, between 4 and 6 am. When trucks arrived at the platform, the broilers were unloaded at a repacking area where the platform staff took the broilers out of the cages one by one, quickly estimated their size and weight, and then sorted them into the cages provided by the clients. Interviewees pointed out that the process of assembling, sorting and distribution to the most appropriate markets was to maximise the value of the birds to be marketed. Broilers from different farms were often mixed according to the client’s requirements on breeds and weight. Interviewees reported that industry followed a similar standard for the broilers in the same slaughter-age group regardless of the breeds, and the standard varied between slaughter-age groups. They also pointed out that the customer preference for broiler weight varied among different provinces. Repacked broilers were weighed and recorded and then moved to an area for uploading into the clients’ trucks, separated from the company’s trucks' loading area. Meanwhile, empty company’s cages were sent to an area in the platform for cleaning and disinfection before being used to load chickens at the farm the next time. It was reported that the platform's opening hours were usually from 6 to 9 am, then it was closed, and no chickens were kept at the platform overnight.

The interviewees also pointed out that only the grower companies with a large daily production volume, at least an average of 30,000 broilers per day, could afford to maintain platforms. It was uneconomical for small or medium-sized grower companies to have a platform as it was a costly operation.

3.3.1.1.5 Wholesale live bird markets, wholesalers and brokers

Two types of wholesale LBMs were identified in the study areas, wholesale-only LBMs and mixed wholesale/retail LBMs. Each wholesale LBM had a private management company responsible for daily management of the market, maintaining market facilities on behalf of the market owner and providing logistics services for stall tenants.

The wholesale-only LBMs had a large daily trade volume, up to 120,000 broilers per day. They were only open to wholesalers and retailers, not to the consumers. Their trading hours were usually from midnight till early morning, and most of them closed in the afternoon. Wholesale-only LBMs typically had a large loading area in the market for transport trucks. Slaughtering services were seldom found in the market.

The mixed wholesale/retail LBMs had much lower daily trade volumes than the wholesale-only LBMs, an average of 10,000 to 30,000 broilers. They were mainly open to retailers and buyers from restaurants, hotels and canteens of schools. People who lived near the market also went there for shopping, but the purchase volume was much less than retailers and buyers (no more than 1%). The trading hours of such LBMs were much longer, from early morning till late afternoon. In addition, the LBMs often provided slaughter services through the slaughtering stalls as the restaurants and canteens preferred the live broiler slaughtered at the market.

The stall setting in both types of wholesale LBMs was similar, with half-open sheds with metal fences, simple watering and feeding facilities. The broilers were loaded in the shed when they arrived in the market, and they could move freely on the ground within the shed.

Two types of wholesalers were identified in the study areas: primary wholesalers and secondary wholesalers. Primary wholesalers generally bought more substantial quantities of live yellow broilers at one time, directly from the grower companies or from the independent farmers, then sold them to the secondary wholesalers and retailers. They usually had stalls in the wholesale-only LBMs to operate the trading activities. Secondary wholesalers were the groups running mixed wholesale/retail LBMs. They bought yellow broilers from primary wholesalers or directly from independent farms, then sold them to retailers, restaurants and canteens. Interviewees reported that some primary and secondary wholesalers run the stalls in more than one LBMs.

Brokers were the people based in the production areas who partnered with the wholesalers but operated independently from the grower companies. They helped wholesalers to select the source of yellow broilers among local farms according to their procurement demands. Brokers charged a service fee from the wholesalers based on the number of broilers they purchased. They paid regular visits to local yellow broiler farms, mainly contract farms and independent farms, to identify good quality broilers which matched the wholesalers' preference or requirements. In addition, they also negotiated the price and shipment schedule with farmers or grower companies on behalf of the wholesalers. It was reported that most wholesalers used brokers as their agents when they buy the yellow broilers directly from farms in the study areas.

3.3.1.1.6 Retail live bird markets and retailers

Retail LBMs were usually located inside or next to a market where people buy their daily fresh food. It was reported and observed that the iron cages were commonly used to house broilers and stacked up to three or four levels in the stall area for showing birds to the customers. Broilers from different grower companies were often housed in the same stall and cage.

Retailers run the stalls in retail LBMs on a daily basis. Interviewees mentioned that it was common that retailers sold a variety of yellow broiler breeds that were most likely from different sources and other poultry species together, mainly ducks and geese. Most retailers would provide a slaughter service if the consumers preferred live chickens killed and defeathered.

3.3.1.2 Interactions and product flow within the value chain

3.3.1.2.1 Production phase

Yellow broiler grower companies controlled the source of day-old chicks (DoCs), feed, vaccine and drugs for contract farms and company-owned farms. It was reported that DoCs came from both the external breeding companies and their own breeding farms or hatcheries, accounting for 30% and 70% of the total supply of DoCs to the companies, respectively. Interviewees pointed out that the companies prohibited their farmers from using other sources of day-old chicks to ensure product quality. There were two feed supply sources: some grower companies had their own feed mills, whereas others bought feed from the feed companies in the market. The proportion of the two feed sources were estimated at 60% and 40%, respectively. The grower company purchased the drugs and vaccines for the contract farms. Interviewees stated that all grower companies banned farmers from buying drugs and vaccines themselves. Grower companies categorised the broilers according to the weight corresponding with the slaughter-age group that the breed belongs.

According to the broiler category, the farmers were paid some bonuses for compliance with producing protocols. A penalty would also apply for non-compliance. Farmers handled normal deaths in the production process with company technical staff's guidance, and carcase disposal was usually conducted in the farm or a place nearby. The company would handle the disposal of abnormally large numbers of dead birds in a sperate place. The companies also collected chicken manure sold to fruit farms and fish feed mills in the local areas.

The independent farmers purchased DoCs, feed, vaccine and drugs from the market. Interviewees reported that all DoCs came from the breeding companies, and there was no self-breeding. Farmers could get free H5-H7 vaccines provided by the government as it is in the compulsory vaccination program. Farmers would dispose of dead birds on the farm or at a place nearby.

3.3.1.2.2 Trading phase

The grower companies managed the yellow broiler sales for their contract farms and company-owned farms. Interviewees pointed out that the contact farmers were not allowed to sell their chickens to other buyers, but only to their contracting company. They also estimated that about 95% of yellow broilers sold entered the live broiler trade networks. Only 5% of them, mostly fast-speed yellow broilers, were sent to the meat processing companies and then sold as chilled chicken meat through the chilled chicken trade networks. We identified two pathways for the live yellow broiler traded from the grower companies to the wholesalers: via the trading platforms (30%) and direct shipment from farms to LBMs (70%).

The independent farmers managed yellow broiler sales by themselves. About 98% of broilers from independent farms were sold to the wholesalers directly. It was reported that 2% of broilers were sold through e-commerce websites or social media platforms by farmers, directly to the consumers after the chickens were culled, defeathered and chilled at the farm. Interviewees described that such online sales appeared in the last three years as the cyber economy and logistics networks had reached China's rural areas.

Participants estimated that about half of live yellow broilers were sold within the areas of Guangxi. The remaining half were bought by wholesalers from other provinces and traded in the area where they were based. Yellow broilers sold in Guangxi were traded through wholesale LBMs, either wholesale-only or mixed wholesale/retail markets and then reached retail LBMs. Interviewees explained that they were unable to estimate the proportion of broilers traded through both types of wholesale LBMs.

Interviewees reported that restaurants and canteens usually asked the slaughter stalls in the market to slaughter and defeather the chickens they bought. Slaughtering is done manually in the stalls with limited machinery assistance. They also confirmed that there were limited meat inspections in market slaughter stalls. Most of the local consumers also preferred the live broilers slaughtered and defeathered in the market. However, it was reported that about 20% of consumers still preferred to take live broilers home from the retail LBMs and kept them for a few days before the slaughtering. This behaviour was explained because consumers were concerned that retailers might add drugs to chicken feed to keep them looking good. Therefore, they prefer to feed chickens for a few days to allow the feed additives to be metabolised or excreted.

3.3.2 Governance of yellow broiler value chain

Yellow broiler grower companies managed about 90% of farms through contract farming, supplying more than 95% of yellow broilers with considerable varieties of breeds to the market. This high volume is advantageous when negotiating prices with other stakeholders. It was reported that there was strong competition for the market share of yellow broilers. Therefore, to avoid competition with large grower companies, smaller grower companies and independent farmers often adopted two strategies: targeting niche market by providing special breeds, or building a strong sales network in a smaller geographic area. Interviewees also pointed out that most of the large grower companies in Guangxi focused on their sales in Guangxi and its surrounding provinces to avoid possible competitions with other sub-branches in the same cooperate and allow them to timely capture market dynamics. Local associations of grower companies were established in some areas but not in all areas. Some large grower companies were also members of the national poultry association.

Moreover, contract farming allowed the grower companies to control the means of production, including DoCs, feeds, vaccines, drugs and veterinary services. Farmers can only use supplies from partner companies unless the company agrees on exceptions. It was found that most companies had sanctions and incentives in place for farmers. The buyback price was specified in the contract, and most companies also provided a bonus for better production performance and shared profits with farmers for a continuous good partnership. Any non-compliant behaviours would incur penalties deducted from the final payment of a production cycle. These included selling chickens to others, buying DoCs from other sources, disregarding vaccination schedules and using prohibited pharmaceutical agents.

According to Chinese regulations, animal owners must apply for animal health inspection certificates if they want to transport live animals to a different county (116). To receive the certificate, the animals need to be inspected by local veterinary officers to confirm their health status. It provides incentives for grower companies and farmers to collaborate with local veterinary authorities on public service delivery, for instance, AI surveillance and compulsory vaccination. In addition, all premises involved in animal production and trading were also required to meet criteria related to animal disease prevention, including infrastructure, facilities and location setting. However, the inspection and enforcement varied among different areas depending on local veterinary authorities' human resource.

3.3.3 Practices related to the risk of H7N9 influenza transmissions

3.3.3.1 Farm level

Participants described that most farms had poor biosecurity management and lacked biosecurity facilities, which was supported by on-site observation.

Through observations, the following practices were identified in some farms: 1) farmers' living areas were next to the farm and shared the same paths and entrance 2) only a netting fence to separate the two areas without facilities for cleaning and disinfection when entering or exiting the farm. Interviewees confirmed that this was a common situation for contract and independent farms in their area. They also confirmed that visitors and vehicles were not required to clean and disinfect before entering the farm. The absence of cleaning and disinfection of the wholesalers' trucks shipped the chickens to LBMs was described as a common situation by interviewees. They also reported that personal protective equipment, such as face masks and gloves, were rarely used by farmers. Interviewees reported that the service companies and brokers also moved freely among the farms and seldomly applied biosecurity measures including cleaning and disinfection, changing clothes and using personal protective equipment.

3.3.3.2 Trading platforms

Interviewees reported that most companies prioritised biosecurity management in the platforms with a substantial investment in the cleaning and disinfection facilities to clean their cages and vehicles. However, two practices were observed in the platforms the researchers visited, which could be biosecurity management gaps. Firstly, most cages from their clients (wholesalers), which were empty for loading birds, were unclean and contaminated by feathers and faeces. Interviewees confirmed that these cages were repeatedly used without cleaning after loading broilers to the live bird markets. Moreover, the cages from different clients were mixed when repacking broilers. Secondly, the wholesalers' trucks were not cleaned and disinfected when they entered the platform, although cleaning and disinfecting transport vehicles after the movements are required by law. Those contaminated trucks shared pathways in the platform with the company's cleaned trucks. Additionally, interviewees stated that most companies that used the platform did not require the clients to clean and disinfect their cages and vehicles, and none of them provided cleaning facilities for use by their clients.

3.3.3.3 Live bird markets

Interviewees claimed that the government biosecurity regulations for LBMs were followed by most wholesale and retail LBMs in the study areas, including closing the market once a month, disinfection once a week and cleaning every day. As a part of the daily management role, the management company of LBM conducted the cleaning and disinfection of the market. It charged the fee to the stall tenants, i.e. wholesalers or retailers. However, interviewees reported that cleaning and disinfection only covered public paths and areas in the markets and did not include the stalls' areas, which is store holder's responsibility. The absence of cleaning and disinfection for space within the stalls was described as a common situation for most wholesale and retail LBMs. However, local veterinary authorities conducted random inspections on stall hygiene practices. Interviewees explained that yellow broilers were kept in the stall until they were sold, making it difficult to conduct a thorough cleaning of the stall. They also reported no facilities to clean and disinfection transport vehicles in most LBMs, and incentives for vehicle cleaning and disinfection were low as this would incur extra costs. Interviewees pointed out that most birds would be kept at least one day and up to five days in LBMs until they were sold, both wholesale and retail. All unsold broilers stayed overnights at the market as wholesalers and retailers did not have an alternative storage place. The turnover period in wholesale LBMs was usually shorter than retail LBMs.

In most retail live bird markets, customers and buyers could step into stalls for selecting the chickens by themselves. While most LBMs provided slaughter services, about 20% of customers still preferred to take lived chickens home for slaughter by themselves. Most LBMs' slaughter services were conducted in an open environment, where customers could witness the slaughtering.

3.4 Discussion

The study provides a detailed description of the yellow broiler production and trading system in Guangxi by conducting a value chain analysis. Stakeholders involved in the yellow broiler production and trading and how they operate and interact within the system were identified and described. The importance of stakeholders has not been described previously or acknowledged in the development of current H7N9 control strategies. Meanwhile, the study also identified the value chain's governance structure and the risk practices associated with H7N9 transmission along the value chain. The study findings draw our attention to the importance of considering the yellow broiler value chain's characteristics in the planning and implementation of H7N9 influenza control strategies.

The study indicated that yellow broilers had a different production and trading system to the white broiler industry in China, industrialised as in most other broiler production countries. The study suggests that the yellow broiler industry's characteristics should be acknowledged and considered in China's control strategies for avian influenza. The current control program did not differentiate the types of meat chickens and implement the same measures without considering different risk levels between yellow broilers and white broilers (105). However, the study found that yellow broilers have a more extended raising period than white broilers that may give them a higher chance for avian influenza amplification and transmission (117, 118). Additionally, they were usually kept in an open environment without protection from wild birds, and this may increase the possibility of virus transmission and the emergence of new viruses. Hence, the surveillance and vaccination program need to be more tailored and targeted to yellow broilers, given they are a significant source of live poultry trade (29). The study revealed that the control program designed for all types of chickens without considering different risk levels might dilute the control resources and hamper control measures' effectiveness.

The grower companies were the most influential stakeholder of the yellow broiler value chain in Guangxi. They played a dominant role in the production phase in resource allocation, setting prices and trade pathways, as well as placing formal and informal rules among stakeholders. It would not be possible without the success of contract farming, where farms were relatively small scale individually but provided a stable production volume in total. Contract farming in yellow broiler production fits well in most areas of Guangxi as most areas of Guangxi are hilly with high population density, which makes it unrealistic to find a vast land to build intensive farm. Hence, it had become a standard model in yellow broiler production in Guangxi that allowed grower companies to control 90% of farms.

Meanwhile, the study also revealed that farmers’ practices heavily depended on the partnering company's intention and management quality. The financial incentives or sanctions under the contract-farming arrangement gave the grower companies better control of farmers’ practices. Such close bonds would help implement disease control policies, whereas the level of compliance also depends on the companies' acceptance and incentives. Therefore, engaging the grower companies in the policy process, not only the implementation phase but more importantly, the design phase, would facilitate the on-farm implementation of avian influenza control measures. However, the grower companies have fewer incentives to influence wholesalers and their practices, although some practices may pose risks to their farms. Therefore, biosecurity management gaps in the trading phase need to be addressed through government-industry partnerships that can provide incentives to grower companies, wholesalers, and retailers (119).

The study also revealed that many yellow broiler farmers were linked together through the contract-farming as the same grower company managed them. However, this characteristic of the yellow broiler value chain has not been fully recognised and considered in designing disease control programs. The official classification of broiler systems in China uses farm size (how many chickens were raised at the same time) to describe the scale of the broiler industry and indicate the level of intensiveness (36). It may apply to the white broiler industry as it is industrialised as in most other broiler production countries; however, it may lead to a misunderstanding of the value chain structure of yellow broilers and underestimate industrialisation of the yellow broiler production. The study showed that most yellow broiler farms' size was under 10,000 chickens but rarely below 5,000 chickens, categorised as small-scale farms in the current classification (36). Whereas they followed the same practices and were linked with each other through the partnering company. Understanding this value chain feature would contribute to conducting effective risk management on avian influenza control.

Third, the study found that trading platforms were a crucial component of the yellow broiler value chain in Guangxi, used by many grower companies to link substantial farms and LBMs both in Guangxi and other provinces. A previous study also indicated that trading platforms were a part of the poultry value chain in other areas of China, while their functions and practices had not been elaborated (67). To the best of the authors' knowledge, it is the first study to investigate trading platforms and their practices in China, even though it is known that the yellow broiler industry had used trading platforms in Guangxi and other provinces since the early 1990s. The study suggests that trading platforms need to be considered for H7N9 influenza risk management and interventions could facilitate breaking the transmission cycles between live bird markets and farms. Short trading hours, no birds staying overnight, and management by a single grower company made achieving rigorous biosecurity more feasible in the platform than in the LBMs. However, the mixing of birds from different farms in the platform, combined with the lack of biosecurity requirements for transport vehicles from LBMs contributed to the high transmission risks. Moreover, there was no specific regulation on trading platform biosecurity management, and thus veterinary authorities seldom conducted inspections in trading platforms. However, grower companies demonstrated their incentives of improving biosecurity in the platform, which would reduce the risk of disease introduction to their farms through movements. Simply management structure of the platform also makes the rigours implementation of biosecurity to be feasible. Taken together, the legislation and the enforcement of biosecurity management at platforms need to be in place and raise awareness of companies.

Surprisingly, trading platforms had received little attention from government animal health management. Surveillance plans at the national and provincial level on avian influenza did not include trading platforms under the category 'types of sampling sites', in which farms and live bird markets were the targets (105). Additionally, officials seldomly conducted inspections in the platform as it is not required by law. However, their roles in the live yellow broiler trading pathway suggested that it is worthwhile to monitor the platforms' disease situations and trade practices. Additionally, surveillance in trading platforms would allow government veterinary agencies to sample the same number of farms more time efficiently and with less human resources than the current approach, which requires staff to be sent to each farm. Then, the resources saved could cover more farms that do not trade through the platforms. Meanwhile, trading platforms' detailed records on source farms, buyers and transport vehicles would provide critical information to complement the current government animal movements recording systems. Thus, they would improve the tracing of products and monitor the changes in trade pathways crucial for outbreaks response and risk management.

Additionally, the study also suggested that a large proportion of yellow broiler farms had limited biosecurity management and facilities, and practices are posing threats of quick transmission across farms and areas if the disease emerged. High-frequency visits of technical staffs, service companies and brokers among farms without cleaning and disinfection increased the risk of spreading in an area when a disease like avian influenza was introduced. The absence of cleaning and disinfection when transport vehicles entered the farms would also increase the chance of introducing risks from LBMs to farms and facilitating transmission across the areas via LBMs. These findings on yellow broiler farms' biosecurity gaps broadly support the work of Li et al. (67) that the expansion of H7N9 infections across the areas in China was possible when trade pathways changed.

Moreover, the study findings are in accord with previous studies in Indonesia indicating limited biosecurity practices and infrastructure in farms across various business types, although the yellow broiler industry in Guangxi was more industrialized (120, 121). Current contract farming arrangements may constrain the incentives for upgrading biosecurity facilities as the agreement indicated farmers were responsible for infrastructure, which often requires significant investment. The advantage of contract farming could be utilised to trigger the improvement of biosecurity at the farm level; however, the limitations of current contractual arrangements required attention and amendment to provide enough incentives for grower companies.

Biosecurity was poorly managed among different types of LBMs, and several gaps hampered the effective risk management of avian influenza. This finding aligns with previous observations in other areas of China, where LBMs' biosecurity practices were generally weak (62, 122). While H7N9 infections in humans have triggered policies towards improving biosecurity in LBMs nationwide (8), some gaps remained at the field level, affecting the implementation of those policies. Firstly, the study showed that the absence of cleaning and disinfection for wholesalers’ trucks had significant negative impacts on the risk mitigation of avian influenza transmission. They linked farms, trading platforms and different types of LBMs. This has important implications for government policies on risk management for avian influenza, where transport vehicles need to be included in the scope of surveillance and risk management programs. Secondly, the stall settings for live chicken trade and slaughter services in LBMs provided customers with a high chance of close contact with live chickens, thus posing a considerable risk of disease transmission between humans and birds. Besides, lack of cleaning and disinfection of areas within stalls and chickens allowed to move in and out for the market closure day also hampered policies' effectiveness on improving biosecurity in LBMs. It is worth noticing that some consumers taking live broilers back home, keeping them then slaughtering the chickens at home also pose a potential risk of zoonotic transmission. Such consumption behaviour requires public awareness campaign to advocate the change. These identified gaps identified can inform the government risk management, which adapts to wholesalers and retailers' practices in LBMs.

The study had some limitations, which need to be considered when interpreting the results. Firstly, the study may not capture all aspects of the value chains of yellow broilers industry and representing all areas of Guangxi. However, the selected areas showed the diversity of industry operations with substantial production and trade volume, and many areas of Guangxi followed their approaches. These results may not be generalisable to the yellow broiler industry in other provinces due to the variations in consumer preference for live meat chicken products. The study still informs provincial level control strategies for Guangxi, for instance, revision of the surveillance that can be adopted in line with the industry characteristics. Additionally, the estimations on the market share of different stakeholders and products along the value chain may not precisely match the situations for all areas in Guangxi.

Further research is required to investigate the possible differences of yellow broiler value chains among different areas of Guangxi and between Guangxi and other provinces to provide more comprehensive evidence for the control of avian influenza. Secondly, there was a potential selection bias when recruiting participants as the government officials recommended them. Although the selection criteria and study objectives were explained thoroughly before selection, it is still possible that participants avoided providing information inconsistent with government policies. To minimise the risk of selection bias, the study triangulated data, wherever possible, by using different stakeholders as a source and the observations at the field. Thirdly, researchers' assessments of on-site observations may have been influenced by the interviewees narrative because they were conducted after the interview. The checklist was used to reduce possible information bias. Moreover, the study was not able to conduct observations in more sites due to the limited resources. However, the researchers triangulated the findings of observations with different stakeholders interviewed to verify the findings wherever possible. Lastly, while the results are currently relevant, rapid changes in the yellow broilers industry occur, both in Guangxi and other parts of China. Governments have been promoting chilled chicken to replace the live chicken trade (MARA China, 2017b), which may reshape the yellow broiler value chains in China, thus triggering different risk pathways. This cross-sectional study could be supplemented by repeat analysis to monitor the industry changes, providing updated evidence for managing potential risks of disease transmission along the value chains. Repeated value chain studies could also be used to evaluate the implementation of control policies.

Further studies are required to address the following aspects of yellow broiler value chain: a) competitions and collaborations between grower companies and the possible influence on governance structure; b) seasonality patterns in yellow broiler production and trade and c) consumption behaviours in relation to yellow broilers and what their impacts on the value chain.

3.5 Conclusion

The value chain analysis highlighted the features of the yellow broiler production and trading system in Guangxi. This study suggested that yellow grower companies, as the dominant stakeholders of the value chain, need to plan and implement H7N9 control strategies. Gaps of biosecurity along the yellow broiler value chain in Guangxi revealed risks of H7N9 transmission that are still present. Targeted measures that adapt to the value chain structure are required to mitigate disease transmission through yellow broiler production and trade.

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Chapter 4. Analysis of the Movement of Live Broilers in Guangxi, China and Implications for Avian Influenza Control

Preface

As well as understanding how yellow broilers are raised and traded in Guangxi (Chapter 3), it is also crucial to understand the spatio-temporal patterns of the movements of yellow broilers to provide a full picture of the potential risk pathways for zoonotic transmission of H7N9 influenza.

Recognising and describing animal movement patterns provides essential information for animal disease control, including surveillance and risk analysis, and allows a more targeted approach for improving the effectiveness of disease control strategies (123-125). However, the daily-updated live broiler movement data are not efficiently utilised to support interventions to control H7N9 and other avian influenza. An in-depth understanding of the movement patterns of live broilers is essential for the implementation of risk-based control of H7N9 influenza.

In this chapter the spatial and temporal patterns of Guangxi's live broiler movements are explored to identify counties with a higher number and frequency of movements that are linked to each other. These findings can help identify potential risk pathways through live broiler movements and their geographical distributions that could be directly used to reduce the risks of H7N9 influenza transmission in Guangxi.

The text of this chapter is identical to the manuscript published in '***Transboundary Emerging Diseases***' with minor amendments. Supplementary materials are presented in Appendix B of this thesis.

This chapter can be found published as:

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Abstract

Most Chinese provinces have a daily-updated database of live animal movements; however, the data are not efficiently utilised to support interventions to control H7N9 and other avian influenza. Based on official records, this study assessed the spatio-temporal patterns of live broilers moved out of and within Guangxi in 2017. The yearly and monthly networks were analysed for inter- and intra-provincial movements, respectively. Approximately 200,000 movements occurred in 2017, involving the transport of 200 million live broilers from Guangxi. Although Guangxi exported to 24 out of 32 provinces of China, 95% of inter-provincial movements occurred with three bordering provinces. Within Guangxi, counties were highly connected through the live broiler movements, creating conditions for rapid virus spreading throughout the province. Interestingly, a peak in movements during the Chinese Lunar New Year celebrations, late January in 2017, was not observed in this study, likely due to H7N9-related control measures constraining live bird trading. Both intra- and inter-provincial movements in March 2017 were significantly higher than in other months of that year, suggesting that dramatic price changes may influence the movement's network and reshape the risk pathways. However, despite these variations, the same small proportion of counties (less than 20%) exporting/importing more than 90% of inter- and intra- provincial movements remain the same throughout the year. Interventions, particularly surveillance and improving biosecurity, targeted to those counties are thus likely to be more effective for avian influenza risk mitigation than implemented indiscriminately. Additionally, simulations further

demonstrated that targeting counties according to their degree or betweenness in the movement network would be the most efficient way to limit disease transmission via broiler movements. The study findings provide evidence to support the design of risk-based control interventions for H7N9 and all other avian influenza viruses in broiler value chains in Guangxi.

4.1 Introduction

China faces severe challenges in controlling avian influenza (AI) given the large population of poultry and humans, their high density and overlapping geographical distribution (126, 127). The recent emergence of new strains of avian influenza viruses (AIVs) such as H7N9 (1), has not only affected the poultry population but also resulted in significant threats to public health (4, 128). The trade of live chickens through live bird markets (LBMs) was identified as a significant pathway for the zoonotic transmission of AIVs (13, 70). Managing AIVs transmission risks across different areas through trading networks and the early detection of AIVs in chicken population are increasingly important (129, 130). However, there is a lack of information about the spatio-temporal dynamics of live poultry trading networks in China (38). These knowledge gaps constrain the development and application of risk-based control strategies for H7N9 and all other AIVs subtypes (67, 71).

Knowledge of animal movement patterns provides essential information for animal disease control, including surveillance and risk analysis, and allows a more targeted approach for improving the effectiveness of disease control strategies (123-125). Social network analysis (SNA) can be used to explore how network configurations affect the dynamics of infectious diseases and to identify premises or areas where risk-based interventions should be targeted (124, 131-133). SNA studies have been conducted on live poultry movements in several countries, including Bangladesh, Cambodia and Thailand (134-136), as well as in China (38, 71). In China, the construction of live poultry movement networks has previously relied on questionnaire surveys and have focused exclusively on poultry movements involving a small number of LBMs (38, 71). Consequently, the findings were unable to capture a comprehensive picture of movement patterns, limiting their application in informing risk-based control interventions.

To address this gap, this study was designed to assess the spatio-temporal patterns of broilers moving out of and within Guangxi Zhuang Autonomous Region (hereinafter referred to as Guangxi) in 2017, based on official movements records. Broilers contribute more than 80% of live poultry production in Guangxi (113) and are primary source of LBMs (137). Additionally, Guangxi's broiler industry has a unique production and trading system comparing with other poultry sectors, which about 90% broilers were traded through LBMs (37, 138). Being the sixth-largest broiler production province in China, Guangxi faces severe challenges in controlling zoonotic H7N9 and other AIVs subtypes (2, 41, 139). It also shares live chicken trading networks with other provinces of China and the neighbouring country Vietnam (38-40). Hence, identifying the most central chicken populations in the Guangxi's movement network that should be targeted to mitigate AIV transmission risks would benefit a much wider area of China and Southeast Asia.

4.2 Materials and Methods

4.2.1 Study area and data source

Guangxi is located in southern China, sharing a land border with Vietnam. Guangxi accounted for 6.7% of the national broiler production in 2017 (36).

More than 90% of broilers produced in Guangxi were yellow broilers, a type of Chinese indigenous chickens used for meat production, with the majority traded through LBMs (37, 138). Additionally, live chickens from Guangxi were traded to several other provinces of China, including Guangdong, Hunan and Yunnan, and the neighbouring country Vietnam, which could further spread the viruses through the trading networks if the AIVs emerged (38-40).

According to Chinese regulations, animal owners must apply for an animal health inspection certificate (hereafter referred to as 'certificate') to transport live animals to a different county (116). With a unique identification, a certificate is granted if the animals pass the inspection to confirm their health status. The certificate, which can only be used once, includes information about the animals being transported, their origin and destination.

The Guangxi Animal Health Inspection Online System (internal government system) records all animal health inspection certificates for all consignments originating from Guangxi. Managed by the provincial veterinary authority, it replaced the previous paper-based certification process on 1 January 2017. This study used de-identified data from this system from 1 January to 31 December 2017.

4.2.2 Data management

A movement was defined as a group of broilers transported in the same vehicle, at the same time, from a source to a destination location. For each record, which represented a movement, six variables were extracted from the online system: the certificate ID, animal species/type, intended date of transportation, number of animals transported, and the County Administrative Code (CAC) of the source and destination county. The CAC is a unique six-digit number for each county of China (140). The study did not consider the source and destination addresses as these were recorded at a lower spatial resolution than counties for only 36.3% and 49.1% of the records, respectively.

A flow chart of the data filtering and cleaning process is presented in Figure 4.1. Out of 245,521 chicken health inspection certificates recorded from 1 January to 31 December 2017, 210,812 records had 'broilers' listed as the animal species/type. The other 34,709 records recorded as 'breeding chicken', 'layer' or 'day-old chicks' or 'chicken' were removed from the dataset. Additionally, 1,553 records with invalid, missing or duplicate certificate IDs and 9,663 records with invalid CAC were removed. Movements occurring between locations in the same county (n=32,906 certificates) were also removed. A total of 166,691 records, representing 199,101,036 broilers, remained for analysis.

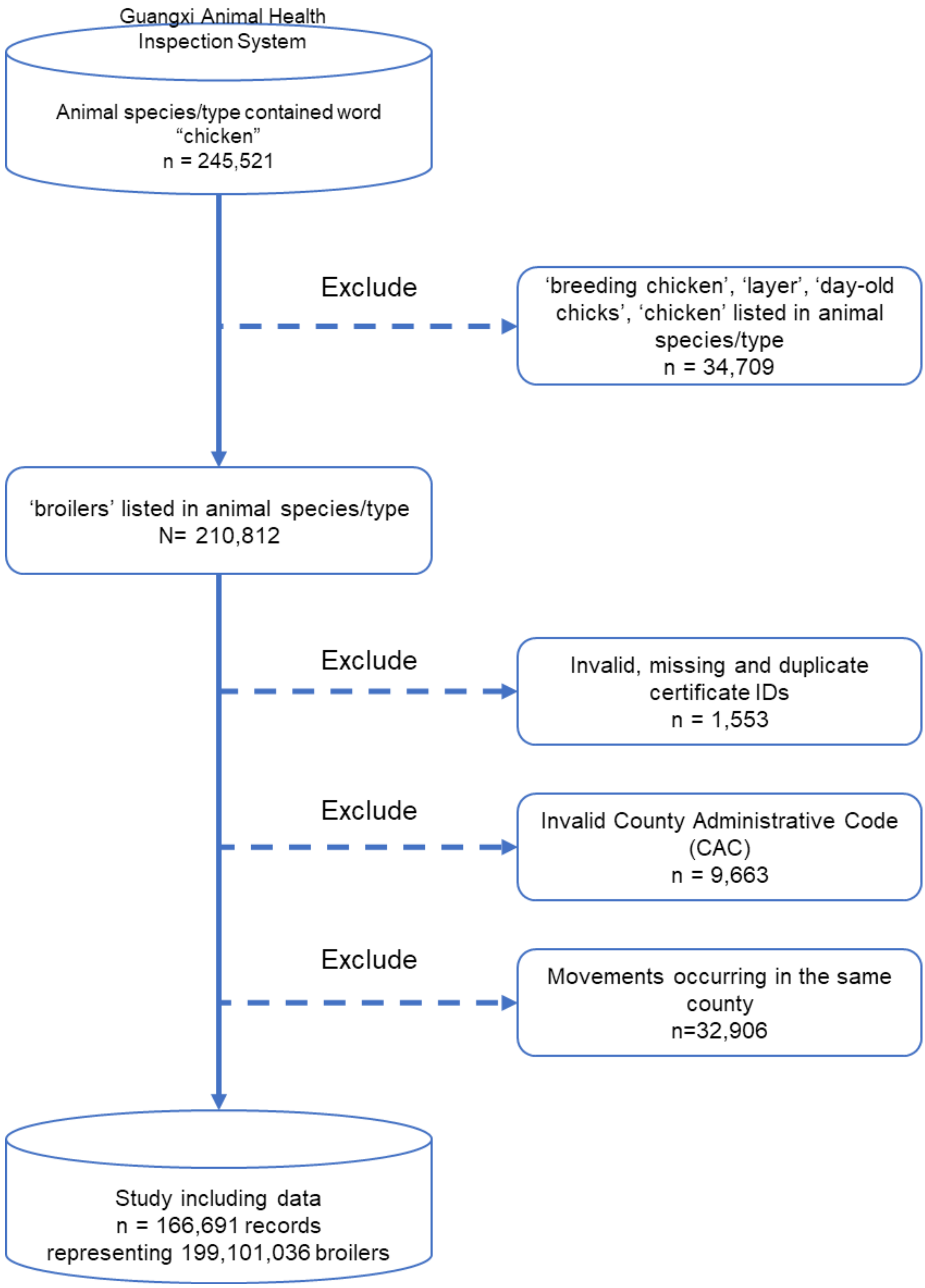

Figure 4.1 Flow chart of data filtering and cleaning of the movements analysis of live broiler chickens in Guangxi, China

4.2.3 Data analyses

Networks were built with counties, in or outside Guangxi, as nodes, and movements, as defined above, occurring in 2017 between two counties as edges. For each movement, the source county was identified as an exporting county, and the destination county was identified as an importing county.

4.2.3.1 Descriptive analyses

Descriptive analyses were carried out for inter- and intra-provincial movements, using the same methods. The following metrics were computed on the yearly and monthly networks, and their distribution was summarised using the median, minimum, maximum and interquartile range (IQR). The total number of edges, movements and broilers transported, the number of broilers per movement and the number of movements and broilers transported per edge were summarised. The number of exporting and importing counties was assessed as well as their associated annual number of movements, broilers transported, and linked counties. The Spearman's correlation coefficient was used to assess (i) whether the number of movements per edge was correlated with the number of broilers transported, and (ii) whether the numbers of counties from and to which a given county imported and exported were respectively correlated with the number of movements into or out of this county. The Euclidian distance (hereafter referred to as 'distance') between counties linked through an edge was also measured using the GPS coordinates of the capital city in each county.

Statistical differences among the number of movements in each month were tested with a Chi-squared goodness-of-fit test. To test the stability of monthly movement networks, the exporting and importing counties with more than 365 movements in the year (i.e. indicating an average of one or more movements per day) were filtered, and the proportion of their monthly movements over total movements in that month were assessed.

Subsequently, the number of months during which each edge occurred was calculated. Edges were grouped according to the number of months they occurred, then the number of edges, movements and broilers moved were summarised for each group. Edges that occurred in ten and more months were identified as 'high-frequency' edges, and edges occurring three or less months as 'low-frequency' edges. Statistical differences of distances between different frequency edge groups were tested using a Kruskall-Wallis test.

4.2.3.2 Social network analysis of intra-provincial movements

The study assessed the characteristics of the yearly and monthly networks shaped by the live broiler movements within Guangxi. The weight of an edge was the number of movements that occurred through this edge. The number of edges and connected nodes were summarised, and the proportion of reciprocal edges were computed. The definitions of parameters used in the SNA are summarised in Table 4.1.

The total-, in- and out-degree, in- and out-strength and betweenness of each node were calculated to assess the nodes' centrality. Correlation among node's centrality measures was assessed using Spearman's correlation coefficient. Additionally, the correlation between counties' out-degree and the number of counties they exported to outside Guangxi was also assessed using Spearman's correlation coefficient.

The network cohesion was assessed by computing the density, diameter, clustering coefficient, and the number and size of strongly and weakly connected components (SCCs and WCCs). The sizes of the largest SCC and WCC can be interpreted as the lower and upper limits of the maximum epidemic size (141). Disease spread may be promoted in small-world networks (142). We assessed whether the network showed small world properties by comparing the average path length and clustering coefficients of the largest SCC to those of random networks with the same number of nodes and edges.

Table 4.1 The parameters and their definitions used in the social network analysis

Parameter	Definition
Measure of centrality	
Total degree	The total number of nodes to which a node is connected through an edge
In-degree	The number of nodes from which a given node receives an edge (i.e. Number of counties exporting to a given node)
Out-degree	The number of nodes to which a given node sends an edge (i.e. Number of counties importing from a given county)
In-strength	The sum of inward edge weights (i.e. Movements to a county)
Out-strength	The sum of outward edge weights (i.e. Movements from a county)
Betweenness	The frequency at which a node falls between pairs of other nodes on the shortest path connecting them considering the edges' weights.
Measure of cohesion	
Density	The proportion of edges that occur in the network relative to the number that could possibly occur.
Average shortest path	The mean of all shortest path lengths between all pairs of nodes in the largest SCC
Diameter	The maximum length of a short path between any two connected nodes
Clustering coefficient	The probability that two nodes connected to the same node are also connected, account for the direction and weight of edges.
Measure of connectivity	
SCC (Strongly Connected Component)	Subset of nodes in which each node can be reached by any other node following network paths
WCC (Weakly Connected Component)	Subset of nodes in which each node can be reached by any other, ignoring the direction of edges
Small-world property	A network with a higher clustering coefficient than, and a similar average path length as a random network (with same number of nodes and edges).

To assess the effectiveness of targeted control of movements to prevent disease transmission, counties were sequentially removed based on their degree or betweenness. The resulting reduction in the size of the largest SCC in the yearly network was assessed. It was compared with the reduction resulting from the random removal of counties. Simulations were repeated 100 times, and the mean and 2.5% and 97.5% percentiles were calculated.

Descriptive and statistical analyses were conducted using the package 'DescTools' (143), and the SNA used the 'igraph' (144) and 'sna' (145) in R® software (R Development Core Team, 2014). Maps were drawn using ArcGIS® 10.5 (ESRI Inc.).

4.3 Results

Of the 166,691 movement events in Guangxi province analysed in 2017, the destination of 30.9% were other provinces, representing 49.3% of all broilers transported. The remaining movements were between Guangxi counties (Table B.1).

4.3.1 Broiler movements from Guangxi to other provinces

In 2017, 1,664 edges were identified from 70 out of 111 Guangxi counties to 389 counties in 24 other provinces. The distribution of movements per edge was right-skewed, with a median of three but a maximum of 2,084. The number of movements and broilers transported per edge was strongly correlated ($p<0.0001$, r = 0.876). Therefore, the following analysis focused mainly on the number of movements rather than the number of broilers moved.

Guangdong province received the most movements (77.5%), followed by Guizhou (9.9%) and Hunan (8.6%). The remaining 21 provinces received only 4% of all inter-provincial movements (Figure 4.2). Thirty-four counties (8.9%) (26 in Guangdong, 5 in Guizhou and 3 in Hunan) received more than 365 movements each, representing 82.2% of all inter-provincial movements. Counties outside Guangxi imported from a median of two Guangxi counties (IQR= 1-4, max = 43). There was a strong correlation between the number of movements from each importing county and the number of counties connected ($p<0.0001$, r=0.844). About 90% of inter-provincial movements involved counties distant by less than 470 km (Median=294, IQR 81-390) (Figure 4.3). There were however, a few long-range movements, with 1.4% of them longer than 1,000 km, up to 3,382km.

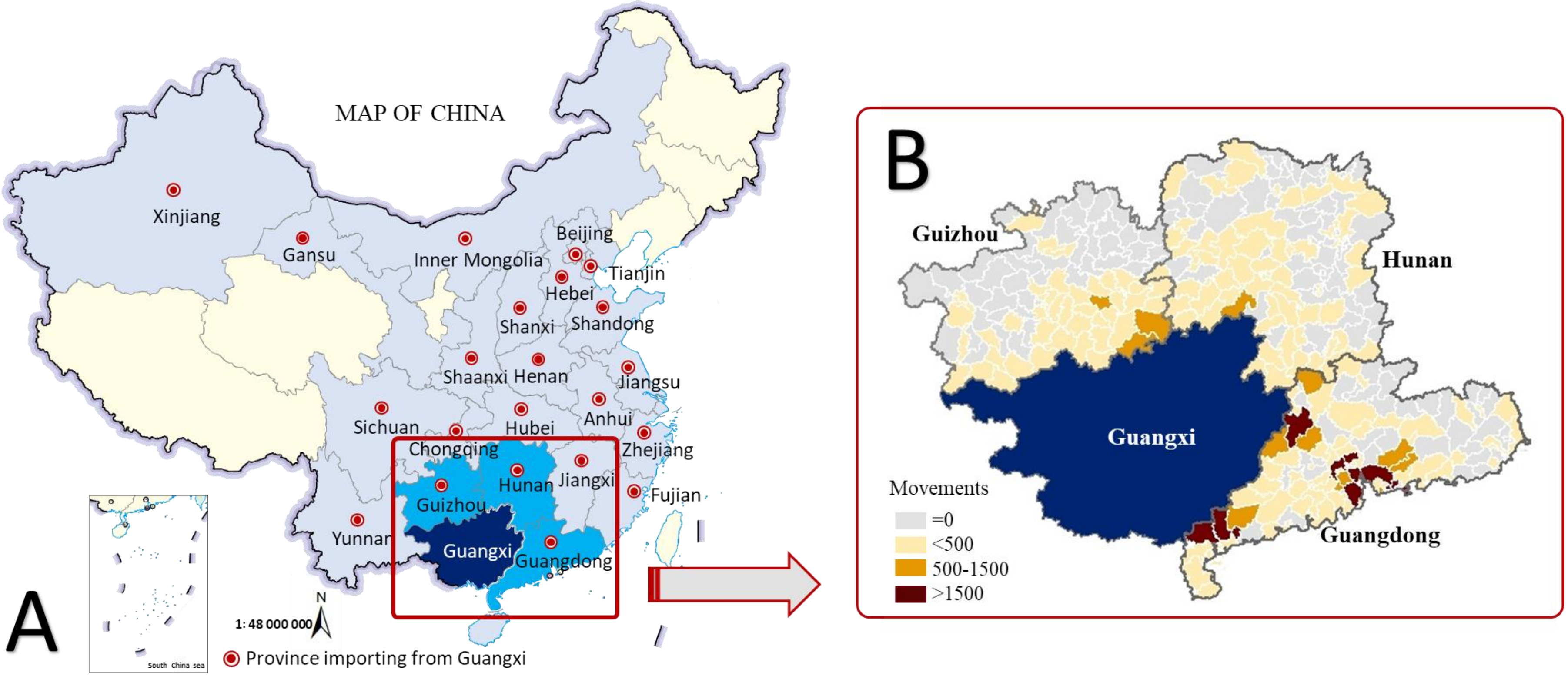

Figure 4.2 A: Provinces that imported broilers from Guangxi in 2017 (provinces importing from Guangxi are coloured in grey with red dot). B: Counties in Guangdong, Hunan and Guizhou that imported broilers from Guangxi in 2017. (Scales represent the number of movements the county importing from Guangxi in 2017)

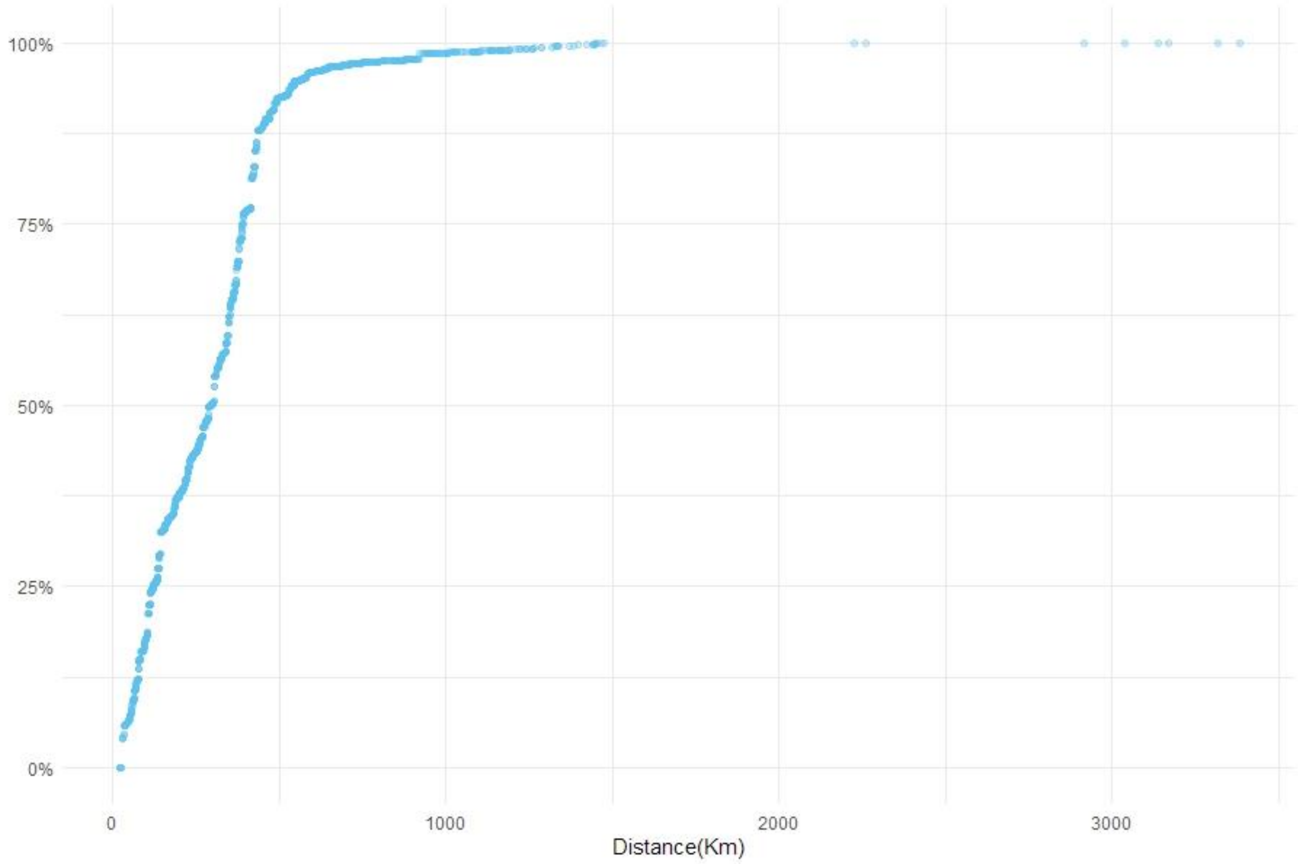

Figure 4.3 Cumulative distribution of movements from Guangxi to other provinces in 2017 as a function of their Euclidian distance

Nineteen counties in Guangxi (17.1%) made more than 365 exports in the year, accounting for 93.1% of all inter-provincial movements. An exporting Guangxi county supplied a median number of 14 counties outside Guangxi (IQR = 4-37, max = 120). There was a strong correlation between the number of movements from each exporting county and the number of linked counties (p<0.0001, r = 0.926).

A significant difference was found among the number of monthly inter-provincial movements (p<0.0001), the highest number of movements occurred in March which was 5,854 movements (11.4% of the annual total, 95 CI: 11.1-11.6%), followed by May (10.1%, 95 CI:9.8-10.3%). The number of monthly edges ranged from 366 in October and November to 716 in March (Figure 4.4). Also, 22.3% of edges (n=160) in March did not occur in other months, which was higher than the proportion of unique edges in any other month (mean = 10.2%).

Each month, Guangdong, Hunan and Guizhou accounted for at least 94% of all inter-provincial movements (Figure 4.4). For importing and exporting counties receiving at least 365 movements in the year, the percentage of their imports or exports of all movements in a month was stable, always higher than 76.7% and 88.3%, respectively.

The total number of edges, movements, and broilers moved were summarised according to the number of months an edge occurred (Table B.2). A small proportion (11.4%, n =189) of edges occurred in ⩾10 months (high-frequency edges), however, these accounted for 80.6% of the total annual inter-provincial movements and 78.9% of the total number of broilers exported from Guangxi. The 189 high-frequency edges involved 28 exporting counties in Guangxi and 67 importing counties in ten other provinces. Most high-frequency edges (95.8%) were directed towards Guangdong (n=144), Guizhou (n=21) and Hunan provinces (n=16). The median distance of high-frequency edges (303 km, IQR 150-390, min = 28, max = 1,449) was significantly shorter (p<0.001) than the median distance associated with low-frequency edges (360 km; IQR 251-597, min = 20, max = 3,382).

In summary, live broilers from Guangxi mainly travelled a short distance to three neighbouring provinces. However, about three-quarters of Chinese provinces received broilers from Guangxi in 2017. A small proportion of importing counties (8.9%) received 82.2% of annual and at least 76.7% of monthly live broiler movements from Guangxi, whilst 17.1% of exporting counties in Guangxi accounted for most inter-provincial annual (93.1%) and monthly (88.3%) movements.

Figure 4.4 Monthly movements and edges (green triangle) of inter-provincial live broiler movements from Guangxi in 2017. Received each month from Guangxi by Guangdong (blue), Guizhou (orange), Hunan (grey) and other provinces (yellow)

4.3.2 Broiler movement between counties within Guangxi

4.3.2.1 Network of all movements in 2017

A total of 1,531 edges were identified within Guangxi, and 24.6% of these were reciprocal (i.e. two counties sending broilers to each other). The distribution of movements per edge was right-skewed (median=5, IQR 2-26, max=11,167). The number of movements per edge was strongly correlated with the number of broilers transported (p<0.0001, r = 0.896). Approximately 90% of intra-provincial movements occurred within 170 km (median = 59, IQR 16-96, max = 535) (Figure B.1).

All 111 counties imported broilers from other counties in Guangxi in 2017, while 90 counties exported broilers. The distributions of in- and out-degree and strength, and betweenness were right-skewed (Table B.3, Figure B.2). There were strong correlations between in-degree and in-strength (p<0.0001, r = 0.727), and between out-degree and out-strength (p<0.0001, r = 0.965). A county could be exporting or importing towards up to 54% of Guangxi counties. Counties' total-, in- and out-degree are presented in Figure 4.5. The in- and out-degree of counties were not correlated (p= 0.094, r = 0.160). The total-degree and betweenness of counties were highly positively correlated (p<0.0001, r = 0.724), indicating that counties with a high number of contacts also tended to be 'bridges' between other counties in the network. Additionally, the top 20 exporting counties of intra-provincial movements also provided live broilers to many counties outside of Guangxi (median=47, IQR: 28 – 55, max: 120) (Figure 4.6).

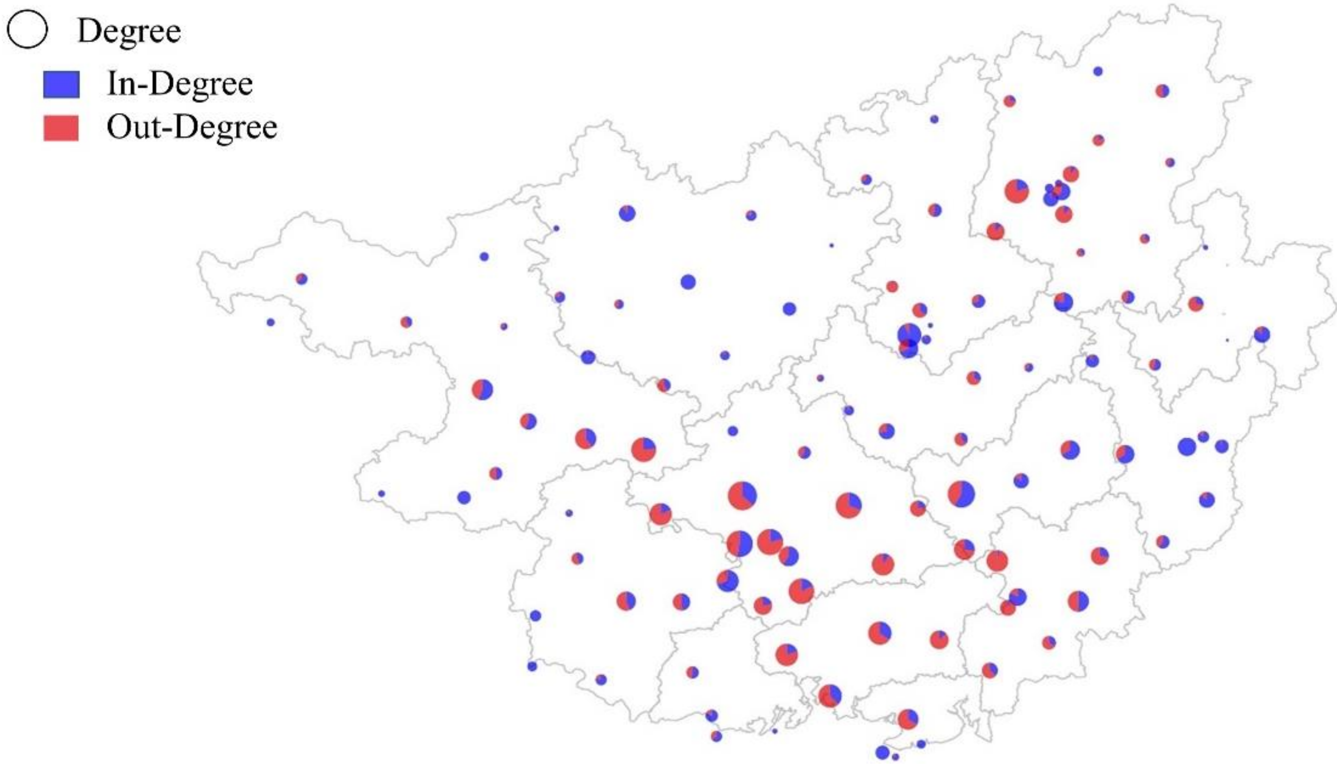

Figure 4.5 Total-, in- and out-degree of each county of Guangxi for the intra-provincial movements in 2017. (The size of the circle indicates total degrees for a county. The colours indicate the percentage of in- and out-degree of total degree.)

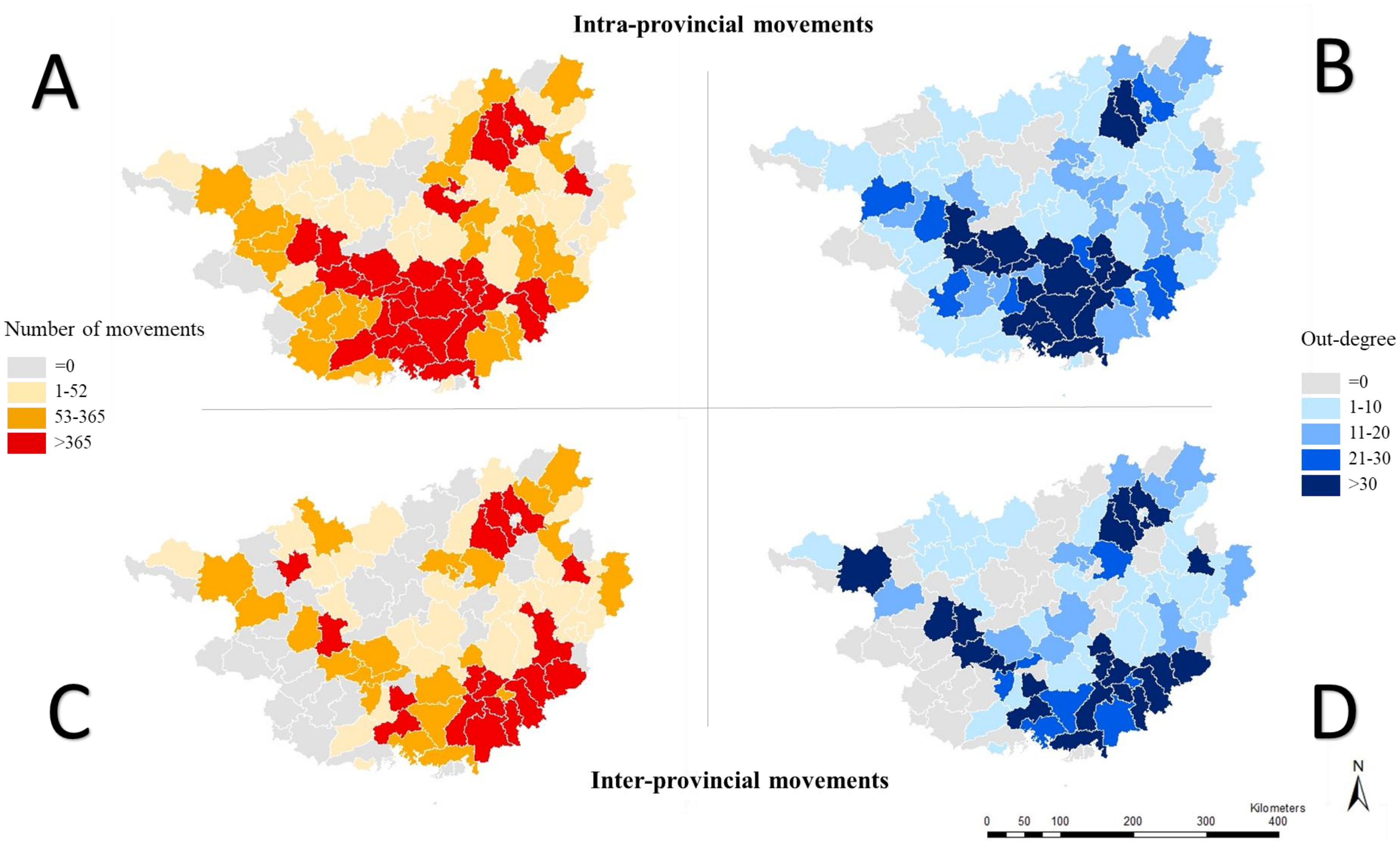

Figure 4.6 Exporting counties engaged in the inter- and intra-provincial movements of Guangxi in 2017 (A and C: Number of movements, B and D: Out-degree, i.e. number of counties connected through exports)

All counties were connected within a unique WCC, with the largest SCC encompassing 87 counties. The remaining 24 counties were directly receiving broilers from the largest SCC. The observed clustering coefficient in the largest SCC (0.49) was approximately 4-fold larger than for random networks (median=0.17, range:0.16-0.18), but the average path length (2.24) was longer than on random networks (median=1.90, range:1.89-1.91), suggesting that the network did not show a small-world behaviour.

To conclude this section, all Guangxi counties engaged in the intra-provincial movements, and the annual movement network showed high connectivity. Similar to the inter-provincial movements (Section 4.3.1), a small proportion of exporting and importing counties contributed most of the live broiler movements within Guangxi.

4.3.2.2 Monthly movement networks

The numbers of monthly intra-provincial movements ranged from 7,598 (6.6% of the annual total) in January to 11,785 (10.2%) in March, and the number of monthly edges ranged from 429 in January to 896 in March (Figure B.3). Significant difference was found among number of monthly intra-provincial movements (p<0.0001). The number of movements and the number of edges in each month was not correlated (p= 0.183, r = 0.413). The number of nodes connected in each monthly network remained similar (min=103 , IQR 104-109, max=111), but the size of the largest SCC also peaked in March (n = 76). The parameters of monthly networks have been shown in Table 4.2.

Table 4.2 Summary of yearly and monthly movement network parameters for intra-provincial movements of Guangxi in 2017

	12-month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of edges	1531	429	583	896	697	624	585	531	448	487	495	597	553
Number of nodes	111	103	109	110	111	109	106	106	106	105	104	103	104
Proportion of reci procal edges	0.25	0.12	0.13	0.19	0.13	0.13	0.14	0.12	0.09	0.17	0.15	0.16	0.14
Density	0.125	0.041	0.049	0.075	0.057	0.055	0.053	0.048	0.040	0.045	0.046	0.047	0.052
Diameter	6	9	8	8	8	8	7	7	9	6	7	8	12
Clustering coefficient	0.48	0.36	0.37	0.40	0.44	0.39	0.41	0.41	0.41	0.37	0.35	0.40	0.43
Number of SCCs	25	55	56	35	61	62	59	69	70	73	64	53	55
Largest SCC size	87	49	53	76	50	47	48	38	37	33	40	50	50

The number of edges, movements, and broilers moved were summarised according to the number of months an edge occurred (Table B.4). A small proportion of edges (18.9%, n=280) occurred in ⩾10 months (high-frequency edges), however these accounted for 89.4% of total annual inter-provincial movements. For importing and exporting counties receiving at least 365 movements in the year, the percentage of their imports or exports of all movements in a month was stable, always higher than 90.7% and 92.6%, respectively.

In conclusion, the network features of monthly intra-provincial movements did not show large monthly fluctuations in 2017 except March.

4.3.2.3 Efficacy of targeted control strategies to limit the transmission of disease via broiler movements

Compared with the random removal of counties, targeting counties according to their degree or betweenness would be the most efficient way to decrease the size of the network's largest SCC. When 21 counties with the highest degree were removed from the network, the largest SCC size decreased by 38%. In contrast, if the same number of counties were randomly removed, the largest SCC size would decrease by an average of 21% (Figure 4.7).

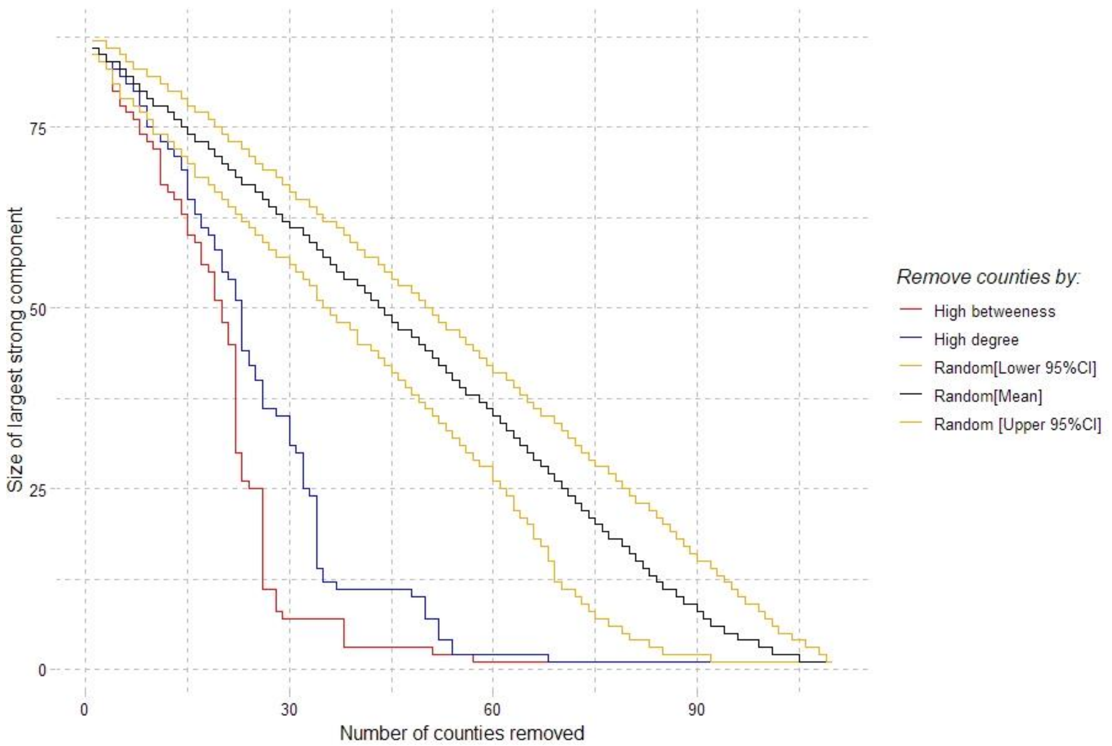

Figure 4.7 Line plots showing the effect of targeted (red and blue) or random (mean in black, 95% CI in yellow) removal of county on decreasing the size of the largest strongly connected component (SCC)

4.4 Discussion

China faces severe challenges in controlling AI in many of its provinces (126, 127). This study further confirmed that Guangxi, with a considerable amount of live broiler movements, faces substantial challenges in AI risk management. The findings indicate that the live broiler trade volume was still large and very active in southern China, despite the closure of LBMs since late 2016 in response to the dramatic increase of human infections with H7N9 (146, 147). The study findings further confirmed earlier observations that public consumption demand for live poultry remained high even during the H7N9 epidemics (83). There are challenges to respond to this situation, and an in-depth understanding of movement patterns would help local veterinary authorities optimise the resources in tackling the challenges.

Previous studies have demonstrated that targeting areas based on movement characteristics would likely have a more significant effect on the control of AI transmission than by applying control measures indiscriminately (97, 136, 148). In this study, a small proportion of exporting and importing counties was found to represent most movements and link the substantial number of counties in Guangxi and other provinces for both inter-and intra-provincial movements. Movements involving these counties occurred almost every month, which contributed to a large proportion of total movements in that month and remained at a similar level over the year. These findings indicate that these counties are significant importers or exporters in terms of amount and frequency, and stability. Therefore, there was a higher risk of bi-directional transmission of AIVs through these counties to a broader area both within and out of Guangxi, particularly considering AIVs transmission risks through transport vehicles are commonly observed in China (129, 146). It makes sense for these counties to be treated as critical control points in AI risk management.

Interestingly, most of the major exporting counties in the intra-provincial movements also linked a considerable number of counties in other provinces through inter-provincial trade, indicating their importance in terms of connectivity in the broiler movement networks and the need for adequate resources to strengthen on-farm surveillance. Surveillance targeting these areas is likely to be more effective in achieving early detection than mass surveillance in Guangxi. Additionally, promoting farm biosecurity could be initially targeted in these areas, considering huge marginal benefits resulting from the intervention. Local growers would find it is more appealing, thus improving compliance. It would also maximise the on-farm biosecurity effects, which were recognised as a significant challenge in the risk management of AI in China (149, 150).

In comparison, major importing counties could be considered priority areas for strengthening biosecurity in LBMs and other trade premises. These counties are most likely to be a major area for live broiler consumption or a trading hub. Thus, the rigorous implementation of biosecurity for trade premises and vehicles in these counties would significantly increase the chance of preventing AIV transmission within poultry and between poultry and people. Meanwhile, it is worth closely monitoring disease emergence in those critical importing counties for early warning and intervention, thus minimising the scale of spread.

A high clustering coefficient (compared with the random network) and a large size of largest SCC (87 out of 111) were observed in the yearly intra-provincial movement network, which suggested high connectivity among counties in Guangxi movements. If a disease was introduced to a movement network with high connectivity, it was likely to spread via the participating nodes (151, 152). Besides, the largest SCC size in each month also contained a large number of counties (IQR=40-50). Hence, the results indicate that Guangxi faces a tremendous challenge to control the spread of AIVs through broiler movements to a large geographical region if AIVs are introduced to any county of Guangxi. Consequently, control of the introduction risk needs to be prioritised in the AI risk management in Guangxi.

The current study results highlighted that implementing control measures specifically in counties with a higher degree or betweenness in the intra-provincial movement network would help decrease the potential disease spread in the movement network than randomly implementing control measures in counties. It further confirms previous findings that control measures targeting nodes with the highest centrality in the movement network resulted in a more significant reduction in the magnitude of a potential epidemic (124, 131, 153). Therefore, the study implied that emergency preparedness and response measures need to be undertaken in these counties first when an outbreak occurs in Guangxi or other import areas. This strategy is likely to be more cost-effective than taking measures, such as movement control, in all counties at the same time. This strategy would also be likely to facilitate compliance with the measures as it limits the disruption to business caused by implementing the control measures.

The spatial pattern of Guangxi live broiler movements also indicates that the risk of H7N9 transmission was presumably higher with neighbouring provinces than other provinces due to the greater movement frequency between these. This study also showed long-distance movements (>1,000 km) existed in Guangxi's live broiler movements, which is consistent with previous studies' observation on long-distance live poultry movements in China (38, 71, 130). However, the percentage of edges involved in long-distance movements was relatively small (5.7%) and were mainly low-frequency movements, which have not been reported in previous studies involving cross-sectional studies using surveys. The potential for widespread distribution of disease through these low-frequency long-distance routines still needs to be paid attention.

Both intra- and inter-provincial movements in March 2017 were significantly higher than in other months of that year. A similar pattern has not been reported in other studies on the live poultry trade in China (38, 39). This result may be explained by the fact that broiler prices in Guangxi and neighbouring provinces had declined steadily since human cases of H7N9 had risen rapidly in late 2016 (154). As a result, growers tried to sell more chickens to avoid further losses (personal communications with broiler growers). Moreover, the proportion of new edges in March was also higher than in other months, potentially increasing the risk of the epidemic occurring in a larger geographical area. It supports Li et al. (67) findings that H7N9 was likely to spread to a wider area due to price changes. As dramatic price changes might influence the movement' network and consequently reshape risk pathways by creating new linkages between counties, real-time price monitoring of live broilers among trading areas could be useful from a risk management perspective, as it could signal possible changes in risk pathways.

Contrary to expectations, a peak in trade during the Lunar New Year celebrations was not observed in this study, even though reported in an earlier study (39). The numbers of movements were not higher in January and February than in other months in 2017. One possible factor might be the closure of LBMs after an upsurge in H7N9 human infections in January 2017, which resulted in reduced consumption of meat sourced from live poultry by the general public (83, 128). It is also possible that chicken products are more affordable and accessible, not particularly during holidays (155).

These findings were based on 2017 data and cannot be extrapolated to other years. A sudden increase of H7N9 human infections in early 2017 and the launch of the compulsory poultry vaccination against H7N9 in July 2017 may have contributed to changes in the demand for live poultry (14, 129). To better understand Guangxi's broiler movement patterns, longitudinal analyses are required to investigate long-term changes in movements and determine if there are seasonal patterns over multiple years. This would provide more comprehensive evidence for managing risks of H7N9 and other emerging infectious diseases through live broiler trade networks.

This analysis did not include broiler movements from other provinces to Guangxi due to limited available data. It may influence the connectivity of some counties in Guangxi, which means some counties may have more links with other counties through importing broilers. However, given that Guangxi's broiler price is always lower than its neighbouring provinces (154), there are likely very few movements from other provinces to Guangxi (personal communication with growers). Thus, these inward movements may have limited impacts on the characteristics of the overall movement network.

Official movement records may not capture all movements that occurred. For instance, trade through unofficial LBMs would obviously not be able to obtain official movement certificates, thus this study likely under-reports movement data. However, the analysis of official movement data still generates unique evidence on movement patterns that other data sources cannot provide due to the trade volume. As a complement to movement analysis, value chain studies are also needed, which could show how the local industry stakeholders do business through formal and informal channels (138).

Notwithstanding the limitations mentioned above, the study still demonstrated that movement data are critical in the risk management of AI. Although H7N9 human infections and the prevalence in poultry have been successfully reduced since H7N9 massive vaccination launched in July 2017 (17, 156, 157), the emergence of other AIVs such as H5N6 highly pathogenic avian influenza and H9N2 in China still pose great challenges to public health and poultry industries (129, 158, 159). These indicate that the importance of efficiently using movement data to inform AI risk management. and should be efficiently used. Most Chinese provinces have a daily-updated database of live animal movements. However, the data are under-utilised to increase the knowledge of live poultry trading patterns and support disease control and prevention interventions. In-depth real-time analyses of movement data would be informative, not only for Guangxi but also for other provinces where the movement records are digitised. Furthermore, it would be beneficial if data from different provinces could be shared and compared, especially for provinces that import live poultry from different areas. A retrospective study is meaningful, but preventive measures based on real-time analysis could better mitigate risks before the occurrence of damaging impacts.

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Chapter 5. A Mixed-Methods Study of Stakeholders' Practices and Attitudes on Avian Influenza H7N9 Vaccination for the Yellow Broiler Industry in Guangxi, China

Preface

China launched a compulsory H7N9 vaccination program in poultry in July 2017 to tackle the growing threats of H7N9 influenza to humans and poultry (10). However, there are different views on whether to continue vaccinating poultry as a long-term routine AI control measure in China, including for H7N9 influenza (129, 160, 161).

Social and economic factors need to be considered when policymakers evaluate the pros and cons of continuing routine vaccination (162). However, very little is known about how Chinese farmers and the poultry industry have adopted and perceived routine mass vaccination. Due to a lack of data, their practices and attitudes have seldom been considered in the debates on AI vaccination policies. In particular, the yellow broiler industry has been neglected in the animal health policy process.

Based on the stakeholders identified as part of the research reported in Chapter 3, their practices, attitudes and motivations regarding H7N9 vaccination in poultry were studied using a mixed-methods design in this chapter. The implications for the H7N9 vaccination policy are also discussed. The findings presented in this chapter provide unique evidence for China's continuing mandatory routine vaccination programs against H7N9 and H5N1 AIVs.

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This chapter can be found published as:

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Abstract

In response to a sudden increase in H7N9 human infections, China introduced a H5-H7 bivalent inactivated vaccine for poultry in Guangxi and Guangdong provinces in July 2017, which subsequently became integrated into the existing compulsory national H5N1 vaccination program from September 2017. Although the vaccination program effectively reduced H7N9 infections in humans and poultry, there are ongoing arguments against continuing this long-term vaccination. These discussions have drawn policymakers to think about the possibility of stopping routine vaccination for H7N9 avian influenza viruses (AIVs) in China, however they have not considered the poultry industry stakeholders' practices on and attitudes towards this vaccination. This study investigated H7N9 vaccination practices in the yellow broiler industry in Guangxi and stakeholders' attitudes on H7N9 vaccination, using a mixed-methods design. The study found H7N9 vaccination was well adopted in the yellow broiler industry in Guangxi regardless of the source of the vaccines. Most stakeholders believed vaccination was the best measure to control H7N9 and H5N1 AIVs, and they showed a strong willingness to continue with vaccination even without government subsidies or freely provided vaccines. The motivations by stakeholders for using vaccines to control H7N9 and H5N1 were different due to the epidemiological differences between the two strains. Understanding poultry industry stakeholders' practices and attitudes on H7N9 vaccination has important practical implications in planning vaccination policies, particularly when considering the possibility of vaccination withdrawal.

5.1 Introduction

H7N9 influenza is a serious threat to public health and demonstrated its zoonotic potential during the outbreak of human infections first reported in early 2013 (1, 21, 84). A spike in cases of H7N9, both in humans and poultry, from September 2016 to May 2017 drew immediate attention from the Chinese government and also concern in the community (14, 163). Moreover, H7N9 highly pathogenic avian influenza viruses (AIVs) emerged in January 2017, resulting in human infections and outbreaks in chickens, which posed an increased threat (17-20). In response, a vaccine containing H7N9 and H5N1 antigens was approved for use in poultry in the Guangxi and Guangdong provinces as a pilot in July and then integrated into the existing national compulsory avian influenza (AI) vaccination program since September 2017 (10). Under this program, the government provides free vaccines, and all poultry producers are obligated to vaccinate their poultry (164).

Several serological studies in different areas of China have demonstrated that H7N9 vaccination has worked well in poultry (15, 17, 157). The mass vaccination of poultry has successfully reduced human infections and reduced the prevalence of H7N9 AIVs in live bird markets and poultry farms in China (17, 156, 157, 165). However, there were arguments that routine mass vaccination might lead to silent infections in poultry and accelerate mutation and variation among AIVs, which could have subsequent severe consequences for poultry and humans (166-168). Additionally, an economic assessment of China's H5N1 routine vaccination program before introducing the H5-H7 bivalent inactivated vaccine suggested that it was a less economically viable option for the government when compared with a stamping-out strategy (169). Debate on the use of mass vaccination as a routine measure to control AI, including H5 strains, has received attention from policymakers and triggered discussion on the possibility of withdrawal of routine vaccination for H7N9 and H5N1 in China (129).

Decisions around vaccination are seldom clear-cut and benefit from a wide range of information (170). Discussion of the need for an AI routine mass vaccination was either from a virological perspective or about the economics of the program from a government perspective (161, 166, 168, 169, 171, 172). Very little is known about how Chinese farmers and the poultry industry have adopted vaccination and perceive routine mass vaccination. Due to lack of evidence, their practices and attitudes have seldom been considered in the debates on AI vaccination policies. In particular, the yellow broiler industry has always been neglected in the animal health policy process, although yellow broilers (a type of indigenous chickens for meat production) are the primary source of live chicken meat in China. Guangxi Zhuang Autonomous Region (hereinafter referred to as Guangxi), as the second largest yellow broiler production province in China, was one of the first two provinces introducing H7N9 vaccination ahead of the national program. Understanding the practices and attitudes of the stakeholders in the yellow broiler industry on H7N9 vaccination is critical when reviewing vaccination policy and implementing actions to achieve better integration with other control measures to mitigate the risk of H7N9 in poultry and humans. Consequently, this study was designed to investigate H7N9 vaccination practices in the yellow broiler industry in Guangxi and the stakeholders' attitudes on H7N9 vaccination using a mixed-methods design.

5.2 Methods and materials

5.2.1 Study Design

A convergent parallel mixed-methods design was adopted in the study, using quantitative and qualitative methods given equal weight to answer the same research question. The quantitative and qualitative data were collected and analysed separately, and results were compared for triangulation and then collated and interpreted together. The study design followed the Good Reporting of a Mixed Methods Study (GRAMMS) guidelines (173). The research process in this study is presented in Figure 5.1.

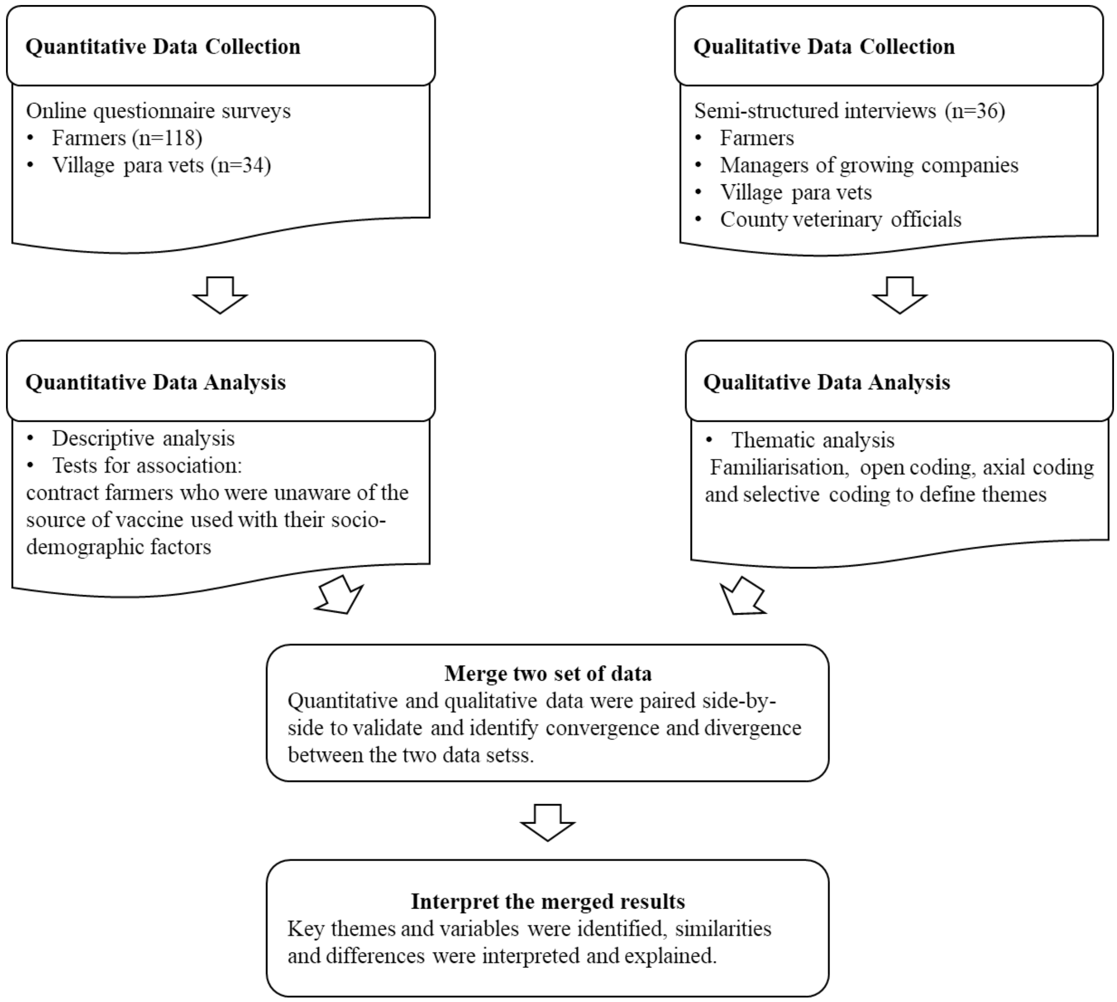

Figure 5.1 Flow chart of parallel convergent mixed-methods, the study of stakeholders' practices and attitudes on avian influenza H7N9 vaccination for the yellow broiler industry in Guangxi, China

The study was carried out in two counties of Guangxi, Xingye and Wuming (Figure 5.2), from May to June 2019. These counties were recommended by the Guangxi Centre of Animal Disease Prevention and Control (CADC). These areas produce a large number of yellow broilers each year and are representative of the yellow broiler industry structure in Guangxi with diversity in farm size, broiler breeds and operational mode.

Figure 5.2 Location of study areas in Guangxi, China

As described in a value chain study on the yellow broiler industry in Guangxi (138), farmers and grower companies are responsible for implementing vaccination. Official veterinarians at the county and township levels are responsible for delivering government-provided vaccines and conducting post-vaccination monitoring with village para-veterinarians' assistance. Therefore, farmers, managers of grower companies, para-veterinarians and official veterinarians were defined as stakeholders for H7N9 vaccination in this study.

5.2.2 Data collection

5.2.2.1 Online questionnaires

A questionnaire with 22 multi-choice questions was developed to gather data on the farmers' H7N9 vaccination practices, attitudes on the H7N9 vaccine and the compulsory vaccination program, and their socio-demographic characteristics. The Para-veterinarian questionnaire consisted of 16 multi-choice questions to collect their attitudes on H7N9 vaccination and their socio-demographic characteristics. Both questionnaires were anonymous and voluntary, and each was estimated to take three to five minutes to complete. The questionnaires were piloted with five farmers and two para-veterinarians, respectively, through face-to-face discussions to ensure questions were in a simple and straightforward format to minimise incorrect interpretation. A brief explanatory message and the questionnaire were circulated among farmer and para-veterinarian social media groups by yellow broiler grower companies and county-level CADCs in the study area to recruit participants.

Online questionnaires were created using a survey tool called 'WJX.cn' and distributed through the social media platform 'WeChat'. A rule in the survey tool was set up so that each IP address could only submit a survey once to avoid potential duplication. English versions of the two questionnaires are presented in Appendix C.2.

5.2.2.2 Semi-structured interviews

The aims for interviewing stakeholders were to: (i) develop an understanding of the variation of vaccination practices in the field; and (ii) gather in-depth qualitative information on their attitudes regarding H7N9 vaccination. The interviews also expanded on the questionnaire surveys by capturing new information that could not be obtained from quantitative data. Four types of participants were recruited: farmers, managers of yellow broiler grower companies, village para-veterinarians and county-level government veterinarians. Two county-level CADCs organised the recruitment through a call for volunteers. Farmers and managers of grower companies were then selected from the volunteers to obtain diversity in production scale and operation mode.

The semi-structured interview approach was employed using open-ended questions (Appendix C.3) to generate thorough descriptive narratives. The main topics covered in the interview included: 1) description of the participants' business/work; 2) H7N9 vaccination practices, including vaccination schedules and management protocols and vaccine source; 3) participants' roles in H7N9 vaccination; and 4) attitudes towards H7N9, and H5-H7 bivalent vaccination programs.

Face-to-face interviews were carried out at the participants' workplaces and took between 40 to 60 minutes to complete and were conducted in Chinese. After a brief introduction of the study and an explicit explanation of the participant's rights, oral consent was obtained from each participant. As most interviewees did not provide consent for audio recording, notes were taken by two people, a note-taker and an interviewer, then compared and integrated afterwards. When discrepancies occurred between the recorded notes, the researcher checked with the relevant interviewee by phone.

5.2.3 Data analysis

5.2.3.1 Quantitative data analysis

Descriptive statistics were generated for variables captured in the surveys by calculating the proportion of the participants with specific answers and their 95% confidence intervals (CIs). Subsequently, we assessed the association between contract farmers, who were unaware of the source of vaccine used on the birds they were raising, and their socio-demographic factors, including age, education level, duration of involvement with the yellow broiler industry, batch size and slaughter-age of birds they were raising. Univariable analysis was initially conducted to determine the association between socio-demographic variables and outcome variables, and odds ratios (ORs) and 95% confidence intervals (CIs) were calculated. Then, variables with a $p<0.25$ were selected to include in a multivariable logistic regression model using a backward process. Variables with a $p<0.05$ were considered significant factors associated with the outcome variable. The statistical analysis was conducted using SPSS version 25.0 (IBM).

5.2.3.2 Qualitative data analysis

In the qualitative data analysis phase, thematic analysis (114) was performed through an inductive approach that derived the codes and themes from the participants' data without theoretical or researcher preconceptions. After removing identified features for the qualitative data analysis process, written notes of individual interviews were imported into NVivo® 12 (QSR International). Firstly, notes were read carefully twice to gain familiarisation with the data, and handwritten notes were made to assist in the coding process. Data analysis was then run through open coding, axial coding, and selective coding in the principle of grounded theory (174). During the coding process, the constant comparative method was used to track commonalities and variations among participants. Themes that provide salient features and insights relevant to the research questions were identified. Data were analysed from original written notes in Chinese. The quotations in the results section indicate the translation of these notes into English verbatim.

5.2.3.3 Mixed-method analysis

After independent analyses of the quantitative and qualitative data, the results were paired side by side according to interest issues. They were then compared iteratively to validate the results and identify convergence, divergence and relationships between the two data sources. Subsequently, the results were integrated into an overall interpretation of the issues of interest.

5.3 Results

A total of 36 stakeholders were interviewed individually, including farmers (n=11), managers of grower companies (n=16), village para-veterinarians (n=4) and county-level official veterinarians (n=5). Meanwhile, 118 farmers and 34 village para-veterinarians participated in the online questionnaire. Socio-demographic characteristics of the study participants are presented in Table C.1 and Table C.2.

5.3.1 H7N9 vaccination practices

5.3.1.1 Vaccine sources and delivery channels

Three sources for the H5-H7 bivalent inactivated vaccine were used in the yellow broiler industry in the study areas, namely ‘government-provided vaccine’, ‘commercial vaccine’ and ‘autogenous vaccine’. The government-provided vaccine is free provided through the compulsory AI vaccination program. Commercial vaccines are government authorised vaccines sold privately, which follow the exact technical requirements as the government-provided vaccine. Autogenous vaccines were developed from pathogenic organisms obtained from birds from the actual flocks vaccinated (175), however these are prohibited by Chinese law. Additionally, participants reported that a combined vaccine of H9N2 and Newcastle disease was another AI vaccine commonly used in yellow broilers, but it was not used in the government compulsory vaccination program.

Among participating farmers, 45.8% (95% CI: 33.6-55.2%) indicated they only use 'government-provided vaccine', 1.7% (95% CI: 0.2-6.0%) only used 'commercial vaccine', and 10.2% (95% CI: 5.4-17.1%) claimed they used both. The interviewees described two scenarios for using both vaccines; (i) using commercial vaccines in the winter-spring season and using government-provided vaccines in summer; or (ii) using government-provided vaccines for the first injection and using commercial vaccines for the second and third injections. No farmers reported using an autogenous vaccine (95% CI: 0-3.1%). However, interviewees pointed out some grower companies in the yellow broiler industry still used H7-H5 autogenous vaccines, but it was hard to estimate the proportion as most of them were reluctant to answer the questions.

Among 112 contract farmers (out of 118 participating farmers), 44.6% of contract farmers (95% CI: 35.2-54.3%) did not know the source of the H5-H7 bivalent inactivated vaccines used in their flocks. No stable logistic regression model could be generated with the data to test the association between contract farmers awareness of vaccine source and their socio-demographics. The results of the univariable analysis are presented in Table 5.1.

Table 5.1 Univariable analysis of 'contract farmer unaware of vaccine source they used' associated with their social-demographic factors (n=112)

Variables	**Unaware vaccine source**	**Proportion (95%CI)**	**OR (95%CI)**	***p*-value**
Total (n=112 †)	**50**	**44.6 (35.2-54.3)**		
Age of farmer (years)				
≤30	3	21.4 (4.7-50.8)	1	0.054
31-40	32	54.2 (40.8-67.3)	4.3 (1.1-17.2)	
>40	15	38.5 (23.4-55.4)	2.3 (0.5-9.6)	
Education (years)				
≤9	26	40.6 (28.5-53.6)	1	0.323
>9	24	50.0 (35.2-64.8)	1.5 (0.7-3.1)	
Duration of involvement with the yellow broiler industry (years)				
<3	6	35.3 (14.2-61.7)	1	0.514
3-10	25	43.1 (30.2-56.8)	1.4 (0.5-4.3)	
>10	19	51.4 (34.4-68.1)	1.9 (0.6-6.3)	
Batch size (birds)				

Variables	Unaware vaccine source	Proportion (95%CI)	OR (95%CI)	*p*-value
≤10,000	21	35.6 (23.6-49.1)	1	0.042
>10,000	29	54.7 (40.5-68.4)	2.2 (1.0-4.7)	
Slaughter-age of bird raised (days)				
60-80	8	61.5 (31.6-86.1)	2.3 (0.6-8.7)	0.424
81-110	12	41.4 (23.5-61.1)	1	
>110	30	42.9 (31.1-55.3)	1.1 (0.4-2.6)	

Note: † 112 participants (out of 118) are contract farmers who are partnering with grower companies to raise yellow broilers

5.3.1.2 Farmers' vaccination operations

Interviewees reported that the vaccination schedule for yellow broiler was consistent with the government recommended vaccination protocols; however the industry made slight adaptions for three different slaughter-age groups. The recommended vaccination schedules were: two inoculations for fast-speed (60–80 days) and mid-speed (81–110 days) growing yellow broilers. The first injection was given when the birds were 10 to 15 days of age, and the second injection when they were 25 to 35 days of age. Slow-speed (>110 days) broilers were given a third inoculation at around 45 to 55 days of age. It was also reported that different grower companies might vary the vaccination schedule, but the schedule usually ranged within the timelines mentioned above. Interviewees also reported that some companies used a different vaccination program in winter-spring seasons involving adding one more inoculations for mid-speed broilers. 82.8% of respondents (95% CI: 74.1-88.6%) knew the recommended vaccination schedule, which matched the slaughter-age of the broilers they raised.

5.3.1.3 Grower companies’ vaccination management

Interviewees reported that the grower companies selected and delivered the vaccines and arranged their contract farms' vaccination schedule. They also reported that most large-scale grower companies managed vaccine procurement through their headquarters and the local sub-branch had limited input into the vaccination protocols of farms within their area. All interviewed grower companies stated that they required their contract farms to use H5-H7 bivalent inactivated vaccines provided by the company, and other sources were prohibited. Grower companies closely monitored the vaccination implementation by checking the farm’s vaccination logbook, undertaking random inspections of the vaccination practice, and regular antibody testing of a sample of birds. Most companies had zero tolerance to non-compliance with the vaccination program, and either a financial penalty or contract termination would be applied if growers were not following the company’s protocols. Interviewees described some companies using the AI antibody test results for a farm as a performance indicator for their technical staff, who provided daily guidance to the farmers.

We do everything for them [contract farmers], set up vaccination schedules, arrange delivery and do testing. They only need to follow our guidelines and promise not to buy vaccines or drugs themselves. (Manager 5)

The company makes the rules that our farmers can only use the vaccines from the company. We take it very seriously, and if they use the wrong vaccine, we are the ones to pay the price. (Manager 14)

5.3.2 Perceptions of H7N9 risks to farms

The study showed that most farmers and para-veterinarians attached importance to the control of H7N9 in yellow broiler farms. 94.1% of farmers (95%CI: 88.2-97.6%) strongly agreed that H7N9 was a prioritised disease to be controlled for the farm, and 94.1% of participating para-veterinarians (95%CI:80.3-99.3%) shared the same opinion.

We all paid the price for H7N9, the worst time for us was late 2016 and early 2017. I have to treat it seriously as there is no other choice. Nobody wants it to come again. (Farmer 7)

Farmers pay attention to H7N9 control, many news on TV talking about human deaths and the closure of live bird markets. The government ran some awareness campaigns, so did grower companies. I never saw chickens dying from H7N9, but I believe from these sources that it impacts on health. (Para-vet 1)

Furthermore, the study found that the grower companies also treated H7N9 very seriously and had prioritised the control of H7N9 in their grower management. Subsequently, their motivations for prioritisation of H7N9 in their production management were explored. Interviewees explained that the reoccurring H7N9 human infections stimulated consumers' concern about the safety of chicken products and resulted from LBMs' closure in many areas. These closures had a significant impact on the yellow broiler industry as most sales were through LBMs. The participants believed the yellow broiler industry would suffer significant financial losses if H7N9 human infections re-emerged. Therefore, grower companies stated that they had to pay great attention to preventing H7N9, although they seldom observed or heard evidence of clinical disease with H7N9 in yellow broilers.

Like many other yellow broiler grower companies, we suffered a long deficit period during the fifth wave of H7N9, from October 2016 till April 2017, much longer than previous H7N9 waves. As we signed a contract with farmers to guarantee their profit, the losses from H7N9 were all on the company's shoulder. The costly lessons taught us to pay great attention to the control of H7N9. (Manager 4)

The study identified another two subtypes of AIVs the yellow broiler industry was concerned about in addition to H7N9, namely H5 and H9. The percentages of participating farmers that firmly believed that H5 and H9 should be controlled/prevented on their farm were high, 94.9% (95%CI: 89.3-98.1%) and 92.4% (95%CI: 86.0-96.5%), respectively. Interviewees also confirmed that grower companies were concerned about the impact of H5 and H9 in their production management but with different motivations. As H5 and H9 AIVs can cause outbreaks in the broiler population with resultant high mortality, the control motivations were illustrated in three aspects: cost of outbreak management, company's partnership with farmers and company's reputation in the market.

If any of our farms got it [H5 or H9 AIVs], we not only paid the price of that farm, culling, disinfection … those works are very annoying, and the company needs to find extra labour to do it. In addition, we also need to do the same thing for neighbouring farms and test our other contract farms. All of these need money and people. (Manager 5)

Farmers would complain if their broilers got AI, they blamed the company. Bad words always passed quickly among farmers. (Manager 11)

Most of our clients [wholesalers] are using local brokers to identify good quality broilers for them. Local brokers are well aware of the situation on farms. If any farm had a problem, they would know it quickly somehow. The yellow broiler industry is a kind of small world, and it will definitely affect our sales if any of our farms had AI. (Manager 13)

Interestingly, interviews revealed that some farmers were not able to differentiate between the subtypes or were not interested in doing so.

I heard about the name of three types of AI, but I do not know the difference. I do not think the differences matter. If my chickens got it, it is a significant loss for me, not only my chickens will be culled and also my neighbours. (Farmer 9)

Only some farmers with long growing experiences are probably aware of the different types of AI, but they may not know the differences. Different types are the same for farmers. We did not highlight subtypes when we talk to farmers, and we just called AI. (Manager 5)

5.3.3 Attitudes on H7N9 vaccination

5.3.3.1 Role of the vaccine in the control of avian influenza

92.4% of participating farmers (95%CI: 86.0-96.5%) strongly agreed that vaccination was the best way to control avian influenza, with 94.1% (95%CI: 80.3-99.3%) of Para-veterinarians holding the same opinion. The study found three motives that explained farmers' strong support for vaccines: 1) free government-provided vaccine and affordable price for the commercial vaccine; 2) an adequate level of protection; 3) not aware of other options.

The cost of AI vaccines is a tiny part of the production cost. The cost of all vaccines for a chicken is about 0.3 Chinese Yuan [equal to 0.04 USD], AI vaccine is cheap and only a few cents per dose. My chickens always passed the company's antibody test, so I assume the vaccine's quality is acceptable. (Farmer 4)

I do not know whether we have another way to prevent AI. It is also the message that my company keeps telling us, vaccination is essential. (Farmer 9)

Grower company managers also agreed that vaccination was the best way to control AI under the current circumstances because the vaccines: 1) have a regular update of the strains incorporated; 2) are of reliable quality, and 3) involve fewer costs compared with upgrading on-farm biosecurity.

Virus strain of AI vaccine was updated almost every two years to keep up with virus mutation. From our practices, we found it protected yellow broilers well. (Manger 5)

AI vaccines are relatively cheap, they only shared a small portion of our growing costs. Most importantly, vaccination is much cheaper than investments in improving biosecurity for company and farmers. (Manager 3)

Interviewees reported that the industry had supported H7N9 vaccination since the release of the H5-H7 bivalent inactivated vaccine. The survey indicated that nearly all farmers (94.9%, 95% CI: 89.3-98.1%) were most concerned about the vaccine's effectiveness, compared with the vaccine price, the number of injections, side effects and following the vaccine choice of other growers. They believed a strong vaccination program would help to regain the consumers' confidence in yellow broilers.

In early 2017, we were quite looking forward to the government approving the H7N9 vaccine to save the markets. Actually, the price [of yellow broilers] went up dramatically after they [government] launched the H7N9 vaccination program. It is a strong signal for the market and consumers (Manager 2)

However, some interviewees from grower companies also recognised the disadvantages of vaccination that might facilitate the mutation of the virus. They mentioned that most yellow broiler grower companies paid close attention to targeting the correct viral clades in vaccines, especially for H5, for which vaccine strains were updated every two to three years. They also appreciated that vaccination was probably not a long-term solution for the industry; however, they believed that vaccination was the best currently available disease control approach.

I studied veterinary science at the university, so I know the vaccine may trigger *virus mutation. However, it is like people having drugs, and it is hard to stop when you start. It is very difficult to convince farmers to put money on improving farm biosecurity when vaccines are cheap and work well so far. From the company's perspective, it is also not realistic for us to invest in farm biosecurity as it would be a substantial investment for the company and hard to see the short-term return. So, we do not have any other choice but focus on vaccination to prevent AI (Manager 9).*

5.3.3.2 Attitudes towards current H5-H7 bivalent vaccination

Farmers showed an adequate level of confidence in the quality of the government-provided vaccine. Among all respondents who claimed they had been using government-provided vaccines (n=66), 87.9% of them (95% CI：77.5-94.6%) stated they had very high or high confidence in the vaccine quality. About 90% of all respondents (95%CI: 82.9-94.6%) stated that they would choose the government-provided vaccines for emergency vaccination if outbreaks occurred.

Interviews elicited the opinions of farmers and grower companies on the pros and cons of government-provided H5-H7 bivalent inactivated vaccines. The positive attitudes were associated with three aspects: 1) lower costs for farmers; 2) government showing support to small farmers; 3) government regulating the vaccine market.

The company overall managed vaccines. Whether they use government AI vaccines or not, they did not charge us as it is in the compulsory vaccination. (Farmer 3)

The government provides vaccines that are showing that the government cares for and supports small farmers. (Para-vet 3)

AI vaccines in the market need to follow the virus strains of government vaccines. I think it helps to reduce the use of autogenous vaccines, good for the industry. (Gov vet 5)

Some interviewees also commented on vaccine concerns: 1) quality of the government vaccine is not as good as a commercial vaccine; 2) unstable quality between different batches of vaccines; 3) waste of public resources as companies tend to use commercial vaccines.

I think the commercial vaccines had better quality than the government ones. The government vaccine was a minimum requirement with the lowest price. You get what you pay for. For example, they use different adjuvant, even if both products are from the same company. (Manager 11)

Government-provided vaccines were generally good. However, we found that some batches of vaccines had low quality, and we told the local CADC. They replaced the products and changed to other suppliers, and then it works well. (Manager 8)

Government-provided vaccines were purchased according to the number of chickens produced. So even if a company uses the commercial one, they still receive government vaccines. It is a waste of public funding. (Gov vet 1)

5.3.3.3 Attitudes on possible withdrawing of government-provided vaccines

68.8% of farmers (95%CI: 59.5-76.9%) stated that they would very likely continue to use the H5-H7 bivalent inactivated vaccine even if the government no longer provided the vaccine free-of-charge, while 55.9% of Para-veterinarians (95%CI: 37.9-72.8%) holding the same opinion. 10.2% of farmers (95%CI: 5.4-17.1%) indicated they would likely continue, and 20.6% of Para-veterinarians (95%CI: 8.7-37.9%) having the same view. While 19.5% of respondents (95% CI: 12.8-27.8%) stated that they would follow the decision made by their contracting company.

Meanwhile, all interviewees from the grower companies believed that grower companies would continue H5-H7 bivalent vaccination even without free government vaccines or government subsidies. Their motives were summarised in four aspects: 1) concerns on the risks of H5 and H7 AI; 2) trust in the effectiveness of vaccination; 3) maintain general public confidence in the safety of yellow broilers, and 4) the low cost of the commercial vaccine.

We paid a high price for H7N9 in 2017. So, I am willing to pay any price to keep our industry away from it. Comparing with that loss, the cost of the AI vaccine is nothing. We cannot give up the vaccination, whether it is compulsory or not (Manager 11).

Interviewees explained that the industry considered H5 and H7 AI threats as high in the short and medium-terms given the poor biosecurity management along the yellow broiler value chains. They considered that the risk of introducing AIVs into the grower farms would still exist and be unpredictable. They believed that vaccination was the most feasible and economical way of controlling and preventing AI. Additionally, interviewees also believed that vaccination would minimise human infections, thus keeping their market access and maintaining consumers' confidence in yellow broilers.

I think vaccination delivers a positive message to the consumer that shows the chickens are safe. It will maintain their interest in buying live yellow broilers. (Manager 6)

5.4 Discussion

The study provides insights into yellow broiler industry stakeholders' practices, perceptions, and attitudes on H7N9 vaccination through a mixed-methods approach. To our knowledge, this is the first study to investigate H7N9 vaccination practices in the yellow broiler industry in Guangxi and to examine local stakeholders' risk perceptions on H7N9 and their attitudes towards its vaccination. The study findings provide unique evidence about the mandatory routine vaccination programs for H7N9 and H5N1 in poultry in China.

This research indicated that the H7N9 vaccination was well implemented in the yellow broiler industry and strongly supported by the industry stakeholders. These results complement evidence to support findings from Zeng et al. (157) and Jiang et al. (15) that H7N9 human infections and the prevalence in poultry were significantly decreased after H7N9 vaccination in poultry. It also reveals that support from the poultry industry would be a critical factor of vaccination policy implementation. The engagement of industry stakeholders in the vaccination policy process is therefore recommended.

There have been debates on the routine long-term use of mass vaccination to control AIVs since H5N1 epidemics in 2003 (129, 160, 161, 169, 176, 177). Some scientists have argued that long-term mass vaccination might lead to silent infections in poultry, accelerate virus mutation and be economically non-viable (166-169). However, this study found that the stakeholders in the yellow broiler industry in Guangxi held different views, although some of them also recognised the disadvantages mentioned above. Most industry stakeholders believed vaccination was the best measure to control H7N9 and H5N1 AIVs, and they showed a strong willingness to continue with vaccination even without government subsidies. The industry stakeholders' practices and attitudes have previously not been included in the scientific debate on the routine long-term use of mass vaccination to control AIVs due to lack of evidence. Considering that they are directly managing the production, their practices and attitudes need to be considered in the policy-making process on vaccination, especially on the possibility of stopping routine vaccination.

Moreover, it is important to understand the rationale of stakeholders' attitudes towards H7N9 vaccination because understanding attitudes alone is insufficient to provide extensive policy-making evidence. Using qualitative research methods, this study identified three motives for stakeholders' positive attitudes towards H7N9 vaccination, i.e. higher perceived risk of AIVs if vaccination is not adopted, concerns on the market reaction from the zoonotic impacts of the disease and the low cost of vaccination.

The study found that industry stakeholders perceived that AIVs were a high risk to yellow broilers. Their risk perceptions were aligned with previous studies that had shown different subtypes of AIVs (H5Nx and H9N2) were still present in China, causing sporadic outbreaks and facilitating mutations in AIVs (17, 18, 178-181). Farmers' attention on the risks of animal infection appears to influence their adoption of disease preventive measures (149, 182). Notably, interviewees believed that improving on-farm biosecurity for yellow broiler farms would cost more than continuing vaccination. However, improving biosecurity could have additional benefits in the long-term by reducing risks of other avian diseases and improving production performance (183). Thus, it would be complementary to ongoing vaccination rather than as an alternative strategy. The study suggests that industry stakeholders' awareness of biosecurity needs to be strengthened with evidence of long-term economic benefits.

Secondly, market reaction was another rationale for stakeholders' positive attitude towards H7N9 vaccination. A previous study suggested that it was difficult to make farmers appreciate the value of vaccines when there were no clinical signs in animals (184). Interestingly, this does not appear to be the case for H7N9, even though it is mostly asymptomatic in the poultry population (2, 185). The interviewees explained that the yellow broiler industry had suffered significant economic losses in the H7N9 epidemics, which later stimulated their willingness to use the H7N9 vaccination. When human infections were reported, the chicken price decreased dramatically (154). This finding confirms that stakeholders' risk perceptions and their choice of vaccination were also associated with economic losses caused by the disease's zoonotic impacts (170). Thus, the prevention of H7N9 human infections was believed to be at the core of using vaccines. After H7N9 vaccination began in July 2017, the market prices of yellow broilers went up quickly and remained at a high level for about a year (154), which further confirmed stakeholders' beliefs in the importance of vaccination to the market.

Additionally, the low cost of H7N9 vaccination was another driver for stakeholders to continue conducting mass vaccination. The study found that vaccine price was not a significant concern when farmers and grower companies chose the H7N9 vaccine. Interviewees reported that less than 1% of the direct production cost was spent on vaccination, even when using a commercial vaccine. The result differs from the findings of studies in Africa and Southeast Asia that showed that vaccine price was one of the factors influencing farmers' decision on adopting AI vaccination (184, 186-188). In comparison, there are substantial government investments in China in vaccine research and development, delivery networks, and post-vaccination monitoring, allowing the vaccine price to remain low. Hence, the low concern regarding AI vaccine price may not apply to other countries. Notably, all indirect costs related to vaccination mentioned above were hard to assess quantitatively but still need to be considered when conducting an economic assessment on AI routine vaccination.

Another important advantage for understanding the stakeholders' rationales for using the H7N9 vaccination is that this information can be used to refine the vaccination strategy's objectives in China. Previous economic assessments on long term AI vaccination have often considered eliminating disease as the vaccination objective, particularly in countries aiming to re-access international markets (161, 169, 170). However, the current study found the industry stakeholders for yellow broilers in Guangxi did not perceive the vaccination objective in that way. They believed the feasible objective to achieve through vaccination was mitigating the risks rather than eliminating AI. Considering the domestic market is the predominant destination for poultry in China, the concern of vaccination effects on international market accessibility does not apply to China. Hence, industry characteristics should be considered during policymaking on vaccination, especially on reviewing or identifying the vaccination strategy's objectives.

The study found that stakeholders' incentives for using the vaccine to control H7N9 and H5N1 AI were different. Vaccination against H5 subtypes is to suppress virus circulation and the number of outbreaks in poultry that could cause substantial direct economic loss for growers. In contrast, mitigation of zoonotic impacts was a critical incentive for industry adoption of H7N9 vaccination. Their different motivations are linked to the epidemiological differences between H7N9 and H5N1 viruses. Despite a long-standing H5N1 vaccination program in China, annual surveillance programs demonstrate that the H5N1 AIVs are still circulating widely in China (41) and elsewhere in the world (189). H5N1 AIVs persist in wild and domestic waterfowl because there is little clinical expression of the virus in these species, and there is limited vaccine coverage in domestic waterfowl (190-192). Mixing of waterfowl and chickens through the live poultry trade and poor biosecurity of LBMs further increase the possibilities of persistence and circulation of H5N1 viruses (15, 129, 138). Sporadic outbreaks of H5 subtypes, which are highly lethal to chickens, have reminded industry stakeholders that the risks are still present despite the relatively high vaccine coverage in chickens against this AIV (41).

While H7N9 is largely asymptomatic in poultry, it has resulted in more human deaths than H5 AIVs (18, 193). A longitudinal survey found that pigeons, ducks and geese were not a significant reservoir of the H7N9 AIV (15) with a national surveillance program demonstrating that H7N9 is mainly restricted to chickens (41). Furthermore, unlike for H5N1 and related viruses, the 2013 H7N9 AIVs is still restricted to China(2). The current level of vaccine coverage for H7N9 among chickens may be very high, and low H7N9 prevalence in pigeons, ducks and geese, indicate that mass vaccination of the susceptible population may even eliminate or severely restrict the transmission of the virus (15, 157, 194).

Understanding stakeholders' different motivations for using the vaccine to control H7N9 and H5N1 AI has important practical implications in discussing vaccination policies, particularly for the possibility of stopping routine vaccination. It is highly likely that H5N1 vaccination cessation would result in a return to significant outbreaks in poultry and may pose a greater public health threat (180, 195). However, after several years of effective H7N9 mass vaccination resulting in no human cases, there may be the potential to eliminate the virus, potentially reducing stakeholders' need for using vaccines. Hence, H7N9 could be an option for piloting the cessation of one type of vaccination in China that the industry could support.

Moreover, the study draws our attention to the importance of considering social and economic criteria when evaluating the possibility of stopping routine vaccination for H7N9 AIVs in China. This also accords with the recommendations on the vaccination exit strategy in the World Organisation for Animal Health (OIE) Terrestrial Animal Health Code (162). Several social and economic criteria need to be explicitly considered for China's circumstance. Firstly, the cessation of vaccination needs to demonstrate economic benefits to stakeholders in the poultry industry given the industrial scale. Secondly, the industry stakeholders support for stopping vaccination would also influence the feasibility and sustainability of the vaccination exit strategy. Lastly, possible public health concerns for stopping the vaccination and associated market effects could also strongly influence the industry stakeholders' attitudes on vaccination cessation.

This research focused on the yellow broiler industry only in Guangxi, therefore, the results need to be interpreted with caution. The findings may not represent the yellow broiler industry in other China provinces as production systems may differ between areas. Others have reported that farmers in remote western areas have different experiences and perceptions of AI than those in eastern densely populated areas (196). Although the findings cannot be extrapolated to all poultry sectors in China, the voices of local farmers and grower companies in the yellow broiler industry provide unique evidence for vaccination policies in China. More research is needed to understand better industry stakeholders' perceptions and attitudes on AI vaccination in different poultry sectors from other regions in China. Their perspectives need to be considered in the debates around AI vaccination and integrated into the policy process.

This study is not intended to recommend stopping or continuing H7N9 vaccination. It further indicates that making decisions on AI vaccination policy in China needs to be cautious and require holistic consideration of virological, epidemiological, social and economic evidence in the policy discussion. In particular, several studies have reported the evolution of H7N9 and H5 AIVs and growing threats from H9N2 AIVs in China (17, 18, 180, 195). These have revealed that the potential risks of AI emergence might also change. Hence, it is also vital to closely monitor AIVs mutations and reassortment and assessing their possible public health impacts to inform AI vaccination policies. Meanwhile, the evolution of AI risks may also change stakeholders' risk perceptions on AI and their attitudes on using the vaccine. In the future, it will be important to explore the potential attitude changes to support policymaking.

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Chapter 6. Benefit-Cost Analysis of a H7N9 Vaccination Program in Poultry in Guangxi, China

Preface

Based on the results of the previous chapters it is apparent that social and economic factors need to be considered when evaluating and improving the H7N9 vaccination policy in China. Decisions on the benefits of adopting a vaccination program require a wide range of evidence, especially economic values (170). However, the economic returns of the H7N9 vaccination program in China have never been adequately assessed.

In this chapter, the economic value of the H7N9 vaccination program in Guangxi was evaluated by assessing the benefits and costs of the program compared to not vaccinating against H7N9. This study considered both the public health and animal health impacts of the vaccination program and took account of both the private and public sectors. The findings presented in this chapter provides evidence to support China's H7N9 vaccination program and evaluates the economic value of conducting routine AI vaccination in China.

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Abstract

China launched a H7N9 vaccination program in poultry, starting from the Guangxi and Guangdong provinces in July 2017, followed by other provinces in September 2017, as a response to a steep increase of H7N9 influenza human infections from September 2016. Since then, H5-H7 bivalent vaccine has been used in the nationwide avian influenza compulsory vaccination program to replace the existing H5N1 vaccine. However, the economic returns of the H7N9 vaccination program in China have never been adequately assessed. This study was designed to evaluate the economic value of the H7N9 vaccination program in Guangxi by assessing the benefits and costs of the program compared to not vaccinating against H7N9.

A benefit-cost analysis (BCA) was undertaken to evaluate the adoption of a vaccination program against H7N9 in each of three consecutive years from July 2017 to June 2020 with the baseline scenario (the absence of H7N9 vaccination in the 12-month period July 2016 to June 2017). Both animal and public health perspectives were included in the BCA framework, and took account of both the private and public sectors.

Benefit-Cost Ratio (BCR) of the three-year H7N9 vaccination program was 18.6 (90%PI: 15.4; 21.8), and total Net Present Values reached to CNY 1.63 billion (90%PI: 1.37 billion; 1.89 billion). The extra revenue generated by the yellow broiler industry comprised 93.8% of the total benefits after adoption of H7N9 vaccination program in Guangxi. While, cost-savings in public health and animal health expenditure avoided were 3.6% and 2.6%, respectively.

Total costs arising from adoption of the revised vaccination program over the three years were CNY 12.46 million (90%PI: 11.49 million; 14.14 million), CNY 34.87 million (90%PI: 31.88 million; 40.06 million), and CNY 44.28 million (90%PI: 39.66 million; 52.27 million), respectively. Sensitivity analysis found the yellow broiler wholesale prices contributed 97.7% of the variance of the total NPV of three vaccination years. The study results demonstrate the significant economic advantage of implementing a vaccination program against H7N9 in Guangxi. It also offers a new set of evidence to China's H7N9 vaccination policy and debates around economic values of conducting routine AI vaccination.

6.1 Introduction

Influenza A (H7N9) virus was first isolated from humans in March 2013 in China (1). It has also been detected in poultry in China in the same month (3) and since then has spread across the country (2). China launched a series of policies to control the disease since April 2013, including: (i) a disease surveillance programme in poultry; (ii) closing live bird markets (LBMs) and controlling the movement of live poultry when infection in people or poultry were reported; (iii) improving biosecurity of LBMs; and (iv) the promotion of poultry meat trade to consumers over live bird value chains. Despite these interventions, there was only partial compliance with these measures (65, 129, 150). H7N9 human infections still occurred as 'waves' during China's winter and spring, with a steep increase in the number of human infections occurring in September (autumn) 2016 (14). The total number of human cases (n=791) in the fifth wave in winter-spring 2016-2017 was more than the total for the previous four waves (n=773, March 2013-June 2016) (2). Highly pathogenic strains of H7N9 virus have been detected in humans and poultry since January 2017, posing an increased threat of infection (197). Moreover, due to consumer concern and the closure of LBMs, H7N9 epidemics caused substantial economic losses to the poultry industry in China, severely affecting the livelihoods of poultry farmers and traders (4).

In response to the evolving situation, China launched a H7N9 vaccination program in poultry, starting with the Guangxi and Guangdong provinces in July 2017, followed by other provinces in September 2017 (10). The inclusion of a vaccine against H7N9 as an H5-H7 bivalent vaccine, replaced the existing

H5N1 avian influenza (AI) vaccine. The prescribed vaccination schedule is for poultry with a growth period over 70 days to be vaccinated twice at a three- to four-week interval and those with a growth period less than 70 days to be vaccinated once (10). As a compulsory program, the government provides free vaccines and all poultry growers are obligated to vaccinate their poultry (164). The reported number of human and poultry infections of H7N9 influenza has reduced since adoption of the H5-H7 bivalent vaccine (15, 129, 165). However, the benefits of using the vaccine as a routine measure to control AI has been debated (166-168). A previous economic assessment of the routine vaccination program against H5N1 in China found that routine vaccination was not economically viable compared with depopulation when only the public expenditures on animal health were considered (169).

Decisions on the benefits of adopting a vaccination program require a wide range of evidence, especially economic factors (170). However, the economic returns of the H7N9 vaccination program in China have never been adequately assessed. Several studies have explored the economic impacts of H7N9 influenza epidemics in China, and their findings have been used to justify investing in the control of H7N9 influenza (76, 101, 198). However, the costs to the poultry industry and public expenditures on animal health were either not considered or were inadequately evaluated in these studies. Hence, an assessment of the economic value of the H7N9 vaccination program in China, considering both animal and public health, are needed to address this deficiency. Such an assessment would provide critical evidence to policymakers when reviewing vaccination policies and control strategies against H7N9 influenza.

Guangxi Zhuang Autonomous Region (hereinafter referred to as Guangxi) is one of the top poultry production provinces of China, contributing 6.7% of the annual national production (36). About 77% of its poultry production is composed of yellow broilers, Chinese indigenous chickens used for meat production, with the more than 90% birds traded through LBMs (37, 138). Live poultry trade in Guangxi poses a significant risk to public health, with both human and avian H7N9 cases reported in Guangxi from 2013 to 2017 (2). In this context, Guangxi was one of the first two provinces introducing H7N9 vaccination ahead of the national program (10). An economic analysis on Guangxi's H7N9 vaccination program would provide valuable evidence for the vaccination policy in China.

Therefore, this study was designed to evaluate the economic value of the H7N9 vaccination program in Guangxi by assessing the benefits and costs of the program from both animal and public health perspectives compared to not vaccinating against H7N9.

6.2 Materials and Methods

To assess the economic value of the H7N9 vaccination program, a benefit-cost analysis (BCA) was undertaken to evaluate the inclusion of a vaccine against H7N9 to the existing AIVs vaccination program over three consecutive years from July 2017 to June 2020 with the baseline scenario (the absence of H7N9 vaccination in the 12-month period July 2016 to June 2017, hereinafter referred to as pre-vaccination). Vaccination years 1, 2, and 3 were defined as: from July 2017 to June 2018, from July 2018 to June 2019 and from July 2019 to June 2020, respectively.

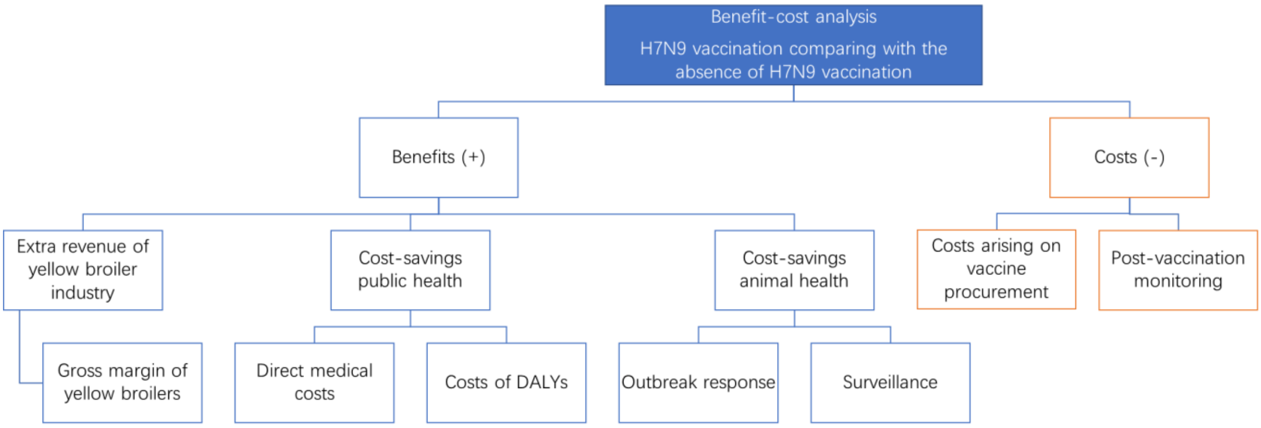
Several assumptions were made for the baseline scenario (before adoption of H7N9 vaccination); namely, the number of human infections and the incidence in poultry in each year of the study would be the same as in the pre-vaccination period, and the gross margin of yellow broiler production would have remained constant, equivalent in each year of the study to the pre-vaccination period.

Before launching the vaccination, several nationwide control measures were implemented after the emergence of H7N9 influenza. The central government had emphasised these interventions in subsequent seasons. Closure of LBMs during outbreaks was the primary measure to minimise the spread of disease, as visiting LBMs was identified as a critical risk factor for human infections (12, 13). At the same time, Chinese veterinary authorities attempted to improve biosecurity in LBMs in order to mitigate risks of human exposure and virus circulation among poultry being sold in the market (8). Unfortunately, these interventions targeting LBMs were not fully implemented and were not successful in halting the spread of H7N9 AIVs to most parts of China (14, 15, 65, 129, 150). Previous studies also showed that the live poultry trade volume was still large and very active in southern China despite the closure of LBMs (146, 147, 199). Therefore, the contribution of these control measures was not considered in the analysis.

The net present value (NPV) and benefit-cost ratio (BCR) were used as performance criteria in the BCA. Currency of the economic values used in this study is Chinese Yuan (CNY), with 1 CNY assumed to equal 0.15 US Dollar (200).

6.2.1 Benefit-cost analysis framework

A BCA framework was constructed (Figure 6.1) to estimate benefits and costs of the H7N9 vaccination program compared to the baseline scenario over a three-year period.



Note: DALYs, disability-adjusted life years

Figure 6.1 Benefit-cost analysis framework for estimating benefits and costs of the H7N9 vaccination program, compared to the baseline (absence of H7N9 vaccination) in the yellow broiler industry in Guangxi province, China

Benefits of the H7N9 vaccination program included three components: 1) extra revenue generated by the yellow broiler industry, 2) cost-savings to public health (direct and indirect costs), and 3) cost-savings of animal health expenditure avoided (outbreak management and disease surveillance). Costs of the H7N9 vaccination program included additional government expenditure on procurement of the H5-H7 vaccine and on H7N9 post-vaccination monitoring. The vaccination protocol (doses and interval) for the H5-H7 bivalent vaccine was the same as for the previous H5N1 vaccination program (105), consequently, the labour cost of vaccination was assumed to remain the same. Additionally, there was no additional cost in vaccine cold chain and delivery as the H5-H7 bivalent vaccine replaced the H5N1 vaccine in the national compulsory AI vaccination program.

Calculations of each component in the BCA framework are described in the following sub-sections. An average discount rate of China in ten years (2011-2020) of 3% (201), was used to convert the present value (PV) in the pre-vaccination period to the future value (FV) in the comparing vaccination period. The values and sources of data used in the model are presented in Table 6.1.

6.2.2 Benefits of H7N9 vaccination program

6.2.2.1 Extra revenue generated by the yellow broiler industry

The estimation of extra revenue focused on the yellow broiler industry. This was because the yellow broilers comprised about 77% of annual poultry production in Guangxi (37). Given that, this estimation of the yellow broiler industry can also allow a fair estimate of extra revenue for the whole poultry industry in Guangxi. Additionally, the production and price data of yellow broilers are available in monthly basis which enable a precise assessment of extra revenue of growers, while such data are not available for the other poultry sectors.

Extra revenue to the yellow broiler industry were estimated by summing the difference in the gross margin of yellow broiler production for the same month of pre-vaccination (GM_{PreVac} and vaccination (GM_{Vac}) phase, using the formula:

$$\sum_{i=1}^{n=12}(GM_{Vac_i} - GM_{PreVac_i})$$

where i = a month between July of the current year and June of the next year.

Gross margin of the yellow broiler industry in a month (GM_i) was given by:

$$GM_i = GM_{perhead_i} \times N_i$$

where $GM_{perhead_i}$ = gross margin per head in month i, and N_i = total number of yellow broilers produced in month i.

Gross margin per individual chicken ($GM_{perhead}$) was calculated by subtracting the cost of production from the revenue per head. Revenue per individual chicken was given by the live yellow broiler wholesale price (per kg) multiplied by the average live weight per individual chicken (kg). Cost of production per individual chicken accounted for the costs of day-old-chick (DoC), feed and labour for production. Cost of feed per chicken was estimated from multiplying the broiler feed price (per kg), the feed conversion ratio of yellow broilers and the average live weight per yellow broiler (kg).

Wholesale price data of live yellow broilers in Guangxi was sourced from the daily price monitoring from an industry website (154). The price of DoC, and feed were extracted from the government's price monitoring (202). Labour cost estimates were sourced from the national agriculture production costs survey (203). The feed conversion ratio of yellow broilers and the average live weight per yellow broiler were used the data from a yellow broiler value chain study in Guangxi (138). Data for the number of yellow broilers produced in a month were available from January to December 2017 and were extracted from the Guangxi Animal Health Inspection System (Internal government database). The number of yellow broilers produced in other months were estimated based on the quarterly growth rate of poultry production in Guangxi (204).

6.2.2.2 Cost-savings in public health

There have been no reported H7N9 human cases in Guangxi since the poultry vaccination program was launched in July 2017. The assumption is that without H7N9 vaccination, the number of human infections in each defined period would have been the same for that from July 2016 to June 2017. Therefore, the direct and indirect costs of human infections in Guangxi from July 2016 to June 2017 were used to estimate the cost savings from avoiding human infections.

All 27 H7N9 human confirmed cases reported from July 2016 to June 2017 in Guangxi were included in this study (9). Confirmed H7N9 human cases were divided into mild, severe without death and severe with death according to the case categories used by the National Health Commission (9).

6.2.2.2.1 Cost-savings due to the direct cost of human infections avoided

Total direct medical costs of human infections in the pre-vaccination period were estimated by multiplying the number of human cases and direct medical cost per case. The discounted value of direct costs of human infections avoided in three vaccination years were then calculated in this estimation.

Data on the direct medical cost per case in Guangxi were not available, hence data were extracted from a previous study conducted in Jiangsu of Eastern China (198). The median and 95% CI values for the three case categories were used to simulate the distribution of direct medical cost per case.

6.2.2.2.2 Cost-savings due to the indirect cost of human infections avoided

Disability-adjusted life years (DALYs) were calculated to assess the indirect burden of H7N9 human infections. DALY is widely used to assess the indirect economic impact caused by a specific disease (205). To calculate the DALYs attributable to H7N9, the H7N9-specific years of life lost due to premature mortality (YLLs) and years lived with disability (YLDs) were estimated (206, 207). The WHO DALY calculation kit was used to calculate the DALYs of all confirmed human H7N9 cases at the individual level in Guangxi from July 2016 to June 2017 (206, 207). The Chinese life-expectancy table from the WHO (2017) was used to estimate the burden of H7N9 in YLLs (207). To calculate YLDs, disability weights of mild and severe H7N9 human cases were set at 0.051 and 0.133, respectively, using infectious disease disability weighting according to the Global Burden of Disease Study (205).

$$DALYs = YLLs + YLDs$$

The human capital approach (HCA) was used to estimate the monetary value of a DALY. This approach is to estimate the value of production losses due to illness, disability or premature death, using non-health Gross Domestic Product (GDP) per capita (208). Although the use of HCA is not universally accepted in the valuation of a DALY, this methodology has been used as it allows animal health and human health aspects to be combined and compared (208).

The total monetary value of DALYs (MVDALYs) was obtained using the equation:

$$\text{MVDALYs} = \sum_{i=1}^{n=27} (NHGDP \times DALY_i)$$

where $\sum_{i=1}^{n=27}$ is the summation of monetary values of DALYs from the first to the twenty-seven cases; NHGDP is the non-health Gross Domestic Product (GDP) per capita calculated by subtracting the health expenditure per capita from the GDP per capita in Guangxi in 2017 (113).

6.2.2.3 Cost-savings of animal health expenditure avoided

An estimate of the expenditure on animal health that was avoided (cost-saving) was generated by summing the expenditures saved by not having to implement an outbreak response or undertaking disease surveillance in

Guangxi province.

6.2.2.3.1 Cost-savings in outbreak response

An outbreak was defined as a positive H7N9 AIV case detected in a location which was reported by the Chinese national H7N9 surveillance program (41). There were no reported outbreaks in Guangxi between July 2017 and June 2020. Therefore, the expenditure on outbreak responses between July 2016 and June 2017 were used to estimate the costs saved in three vaccination years accounting discounting rate. The costs of an outbreak response were calculated by:

$$Cost_{OR} = n_{outbreak} \times CostPC_{OR}$$

The number of outbreaks in poultry in Guangxi ($n_{outbreak}$) was extracted from the national surveillance reports from July 2016 to June 2017 (41). $CostPC_{OR}$, the cost of the outbreak response per individual outbreak, was calculated using the data from the survey of H7N9 influenza control in Guangxi conducted by the Guangxi Centre of Animal Disease Prevention and Control (CADC) (209). The government pays for outbreak response according to the Chinese law (164). The cost of the outbreak response includes poultry culling and disposal, cleaning and disinfection of outbreak site, compensation paid to farmers/traders, and for logistics and human resources. The median, minimum and maximum expenditure were calculated and used in this estimation.

6.2.2.3.2 Cost-savings in disease surveillance

Virology and serology tests were continually conducted in Guangxi since the emergence of H7N9 influenza as required by the national H7N9 surveillance program (41). Following the implementation of the vaccination program, serological surveillance was no longer required. Therefore, cost-savings in disease surveillance using serology considered expenditure avoided serological tests and labour of conducting the surveillance. Although Guangxi continued serology testing after H7N9 vaccination was launched, the objective was to monitor the effectiveness of the vaccination program, therefore, it is considered as post-vaccination monitoring rather than disease surveillance.

The expenditure avoided from virology tests in each vaccination year were calculated as the difference in number of virology samples collected between pre-vaccination year and vaccination year multiplied by the unit cost of a virology test. The expenditure avoided from surveillance labour cost was estimated by multiplying the labour cost per sampling site and the difference in number of sampling sites between pre-vaccination and each vaccination year.

The unit cost of virology test and serology test and the labour cost per sampling site were extracted from the survey of H7N9 influenza control in Guangxi conducted by the Guangxi CADC (209). Median, minimum and maximum values were calculated and used in the BCA. The numbers of virology and serology samples and sampling sites in Guangxi were sourced from data in the national veterinary monthly reports (41).

6.2.3 Costs of H7N9 vaccination program

The costs of H7N9 vaccination program were estimated from two components: additional government expenditure on H5-H7 vaccine procurement and the government expenditure on H7N9 post-vaccination monitoring. The additional government expenditure on H5-H7 vaccine procurement was calculated by Guangxi's government expenditures on H5-H7 vaccine procurement in each vaccination year minus the discounting expenditures on the univalent H5N1 vaccine procurement in the pre-vaccination period. Data on the government expenditures on vaccine procurement in Guangxi were obtained from the public website of Guangxi Government Procurement Centre (210). It is acknowledged that some growers were likely to have purchased vaccines themselves rather than use the government-provided ones; however, no data were available for an estimate of the private expenditure on the vaccine. Thus, it was excluded from the analysis.

The government expenditure on H7N9 post-vaccination monitoring was estimated from the costs of serology tests undertaken in three vaccination years. The costs of serology test were calculated as the total number of serological samples collected in the vaccination years multiplied by the unit cost of a serological test. The number of serological tests in Guangxi was sourced from data in the national veterinary monthly reports (41). The unit cost of a serological test were extracted from the survey of H7N9 influenza control in Guangxi, which was conducted by the Guangxi CADC in 2018 with the participation of all county-level veterinary authorities (209). Median, minimum and maximum values were calculated and used in the BCA.

The vaccination protocol (doses and interval) for the H5-H7 combined vaccine was the same as for the previous H5N1 vaccination program (105), consequently, the labour cost of vaccination was assumed to remain the same.

Table 6.1 Input data used to estimate the benefits and costs of H7N9 vaccination in Guangxi province, China from July 2017 to June 2020, compared to the baseline (absence of H7N9 vaccination)

Note: a. # data is the national level due to lack of Guangxi's data

b. Currency of price data (CNY), 1 CNY = 0.15 USD

c. Pre-vaccination (Before adopting H7N9 vaccination): July 2016- June 2017; Vaccination Year-1: July 2017 –June 2018; Vaccination Year-2: July 2018 – June 2019; Vaccination Year-3: July 2019 June 2020

Input data	Values/distributions	Description and/or source
Monthly yellow broiler wholesale price	Pert (min, median, max)	Xinmu yellow broiler price monitoring (154)
Average live weight (kg) per yellow broiler	1.5	Tang et al. (138)
Monthly day-old-chick (DoC) price	Pert (min, median, max)	Ministry of Agriculture and Rural Affairs (MARA) price monitoring (202)#
Monthly broiler feed price	Pert (min, median, max)	MARA price monitoring (202) #
Feed conversion ratio of yellow broiler	1:2.5	Tang et al. (138)
Labour cost of production per chicken (CNY)	Point estimates: 2016: 4.91 2017: 4.83 2018: 5.29 2019: 5.42 2020: 5.56	National Development and Reform Commission, National agriculture product costs report (203)
Monthly number of yellow broilers produced (2017.1-12) (million birds)	(min, median, max) (14.5, 16.0, 23.1)	Extracted from Guangxi Animal Health Inspection System (internal government system)
Quarterly growth rate of poultry production, Year-over-Year (%)	(min, median, max) (-2.8, 3.5, 23.4)	Guangxi Statistic Bureau (204)
Number of human cases	n=27	Guangxi Health Commission (20)
Mild	6	
Severe	7	
Severe with death	14	
Direct medical cost per	Pert (min, median, max)	Huo et al. (101)

Input data	Values/distributions	Description and/or source
human case (CNY)		
Mild	(3,320; 12,790; 19,750)	
Severe	(56,780; 96,780; 287,140)	
Severe with death	(116,410; 228,650; 549,520)	
Number of reported H7N9 outbreaks in poultry	18	MARA monthly veterinary bulletin (41)
Cost of outbreak response per reported outbreak in poultry	Pert (min, median, max) (10,000; 167,000; 465,000)	Survey on H7N9 influenza control, conducted by Guangxi Animal Diseases Control and Prevention Centre (CADC), participated by all county-level CADCs in Guangxi(209)
Number of virology samples in H7N9 surveillance	Pre-vaccination: 54,778 Vac Year-1: 18,622 Vac Year 2: 22,390 Vac Year 3: 25,030	MARA monthly veterinary bulletin (41)
Unit cost of a virology test	Pert (min, median, max) (20; 78; 120)	Survey on H7N9 influenza control, conducted by Guangxi CADCs (209)
Number of sampling site in poultry surveillance	Pre-vaccination: 7,487 Vac Year-1: 2,711 Vac Year-2: 6,148 Vac Year-3: 7,971	MARA monthly veterinary bulletin (41)
Labour cost per sampling site	Pert (min, median, max) (1,000; 2,000; 5,000)	Survey on H7N9 influenza control, conducted by Guangxi CADCs (209)
Number of serology samples in H7N9 surveillance and post-vaccination monitoring	Pre-vaccination: 141,443 Vac Year-1: 49,040 Vac Year-2: 151,769 Vac Year-3: 233,761	MARA monthly veterinary bulletin (41)
Unit cost of a serology test	Pert (min, median, max) (0.5; 15.9; 100)	Survey on H7N9 influenza control, conducted by Guangxi CADCs (209)
Government expenditures on vaccine procurement (million, CNY)	Pre-vaccination: 90.1 Vac Year-1: 104.1 Vac Year-2: 126.7 Vac Year-3: 137.0	Guangxi Government Procurement Centre (210)

6.2.4 Simulation and Sensitivity analysis

Most economic input variables were entered as distributions rather than point estimates in the analysis model to account for variation and uncertainty with the inputs (Table 6.1). Monte Carlo stochastic simulation (10,000 iterations) using @Risk® (Palisade Student Version 8.0, Ithaca, USA) in Microsoft© Excel® was used to account for variability of output variables. The median values of the output variables and 90% prediction intervals (PI) were calculated using @Risk functions.

Sensitivity analysis was performed to identify the magnitude with which inputs affect the variability of NPV and BCR by examining the contribution to variance. It was conducted using the in-built sensitivity analysis of @Risk.

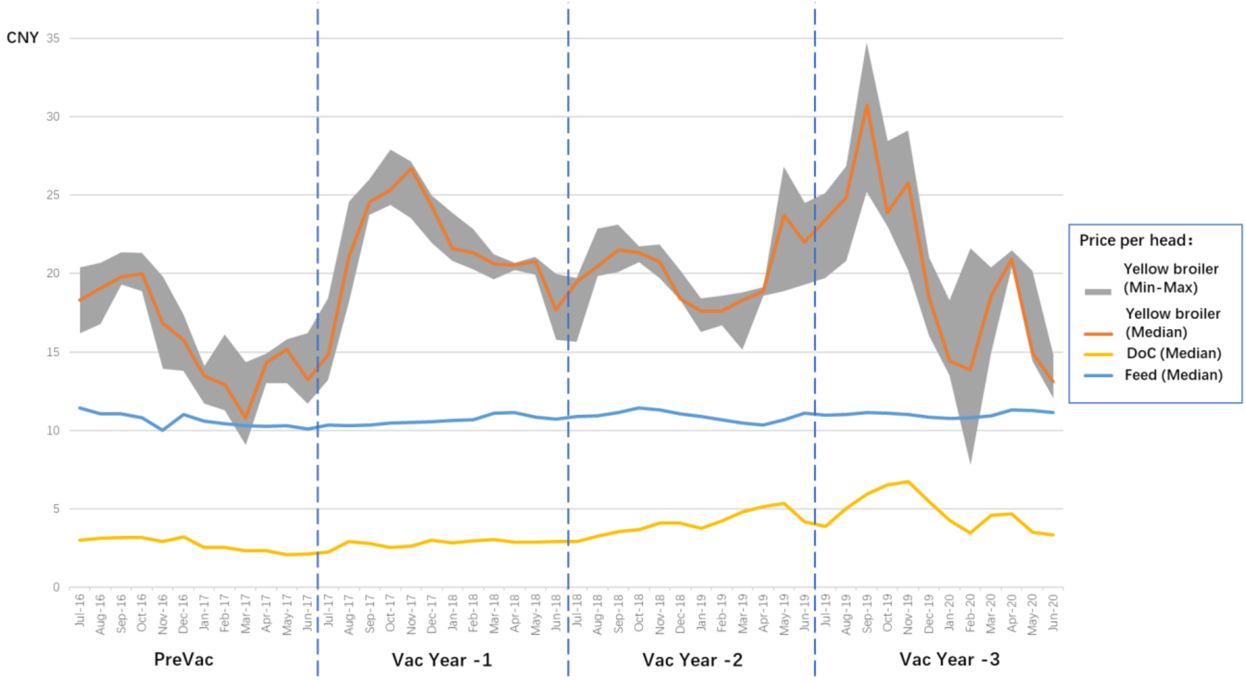
6.3 Results

6.3.1 Benefits of H7N9 vaccination program

The extra revenue generated by the yellow broiler industry comprised 93.8% of the total benefits after adoption of H7N9 vaccination program. While cost-savings in public health and in animal heath were 3.6% and 2.6%, respectively.

6.3.1.1 Extra revenue of yellow broiler industry

The price of yellow broilers, DoC and broiler feed during the pre-vaccination and vaccination periods (July 2016 - June 2020) are presented in Figure 6.2.



Note: CNY, Chinese Yuan (1 CNY = 0.15 USD); DoC, day-old-chick

Figure 6.2 Price of yellow broiler, day-old-chick (DoC) and broiler feed from July 2016 to June 2020

The median gross margin in vaccination Year 1, Year 2 and Year 3 were CNY 1.09 billion (90%PI: 1.00 billion; 1.18 billion), CNY 379.16 million (90%PI: 284.44 million; 469.27 million), and CNY 144.67 million (90%PI: -9.28 million; 295.92million), respectively.

6.3.1.2 Cost-saving in public health

The total median public health cost of Guangxi during the pre-vaccination period (July 2016 to June 2017) was estimated to be CNY 18.57 million (90%PI: 17.06 million; 20.70 million). Of this the median direct cost of human infections in Guangxi was estimated to be CNY 4.49 million (90%PI: 2.98 million; 6.61 million). The total DALYs loss of Guangxi was estimated at 346 life years, which had a monetary value of CNY 14.08 million. The discounted cost-savings in public health for each vaccination year are presented in Table 6.3.

6.3.1.3 Cost-saving of animal health expenditures avoided

The number of virology and serology tests conducted, sampling sites visited and the number of outbreaks in the study period are summarised in Table 6.2. The median cost-saving in disease surveillance for the three years when H7N9 vaccination was implemented was estimated to be CNY 17.60 million, CNY 9.37 million and CNY 4.98 million, respectively. The median cost of the outbreak response during the pre-vaccination period (July 2016 to June 2017) was CNY 3.33 million. Discounted cost-savings in outbreak response in the three vaccination years are presented in Table 6.3.

Table 6.2 Number of virology and serology tests and sampling sites for H7N9 surveillance, number of serology tests for post-vaccination monitoring and number of H7N9 outbreaks in poultry in Guangxi from June 2016 to July 2020

Source: Monthly veterinary bulletin, Ministry of Agriculture and Rural Affairs, China

	Number of virology tests undertaken for H7N9 surveillance	Number of serology tests undertaken for H7N9 surveillance and post-vaccination monitoring	Number of sampling sites for H7N9 surveillance	Number of H7N9 outbreaks in poultry
Pre-vaccination (July 2016-June 2017)	54,778	141,443	7,487	18
Vaccination Year 1 (June 2017-July 2018)	18,622	49,040	2,711	0
Vaccination Year 2 (June 2018-July 2019)	22,390	151,769	6,148	0
Vaccination Year 3 (June 2019-July 2020)	25,030	233,761	7,971	0

The median total cost-savings in animal health expenditures avoided in each of the vaccination years 1, 2 and 3 were CNY 21.17 million (90%PI: 14.39 million; 29.25 million), CNY 13.09 million (90%PI: 8.51 million; 18.97 million), and CNY 8.84 million (90%PI: 4.41 million; 14.72 million), respectively.

6.3.2 Costs arising from adoption of the revised vaccination program

The government expenditure on H5N1 vaccine procurement during July 2016 to June 2017 was CNY90.13 million. The expenditure on H5-H7 in vaccine procurement for the three vaccination years (July 2017-June 2020) was CNY104.09 million; CNY126.74 million and CNY136.99million, respectively. The median expenditure on H7N9 post-vaccination monitoring in each year was CNY 1.21 million (90%PI: 0.24 million; 2.89 million), CNY 3.75 million (90%PI: 0.75 million; 8.93 million), and CNY 5.77 million (90%PI: 1.16 million; 13.76 million), respectively. The median total costs arising from adoption of the revised vaccination program over the three years were CNY 12.46 million (90%PI: 11.49 million; 14.14 million), CNY 34.87 million (90%PI: 31.88 million; 40.06 million), and CNY 44.28 million (90%PI: 39.66 million; 52.27 million) after discounting, respectively.

6.3.3 NPV and BCR

The NPV of the three-year H7N9 vaccination program was CNY 1.63 billion (90%PI: 1.37 billion; 1.89 billion). BCR of the three-year H7N9 vaccination program was 18.6 (90%PI: 15.4; 21.8). The NPV of the H7N9 vaccination program was estimated to be CNY 1.12 billion (90%PI: 1.03 billion;1.21 billion) in the first vaccination year. Subsequently it decreased in the second and third vaccination years, i.e. CNY 377.68 million (90%PI: 282.45 million; 468.38 million) and CNY 131.03 million (90%PI: -22.01 million; 282.46 million).

Table 6.3 Benefits, costs, net present values (NPVs) and benefit cost ratio (BCR) of H7N9 vaccination program in Guangxi from July 2017 to June 2020, compared to the baseline (absence of H7N9 vaccination, pre-vaccination)

Note: Currency of data: in million CNY, 1 CNY = 0.15 USD, discounting rate: 3%

Change in value compared to pre-vaccination	**Vaccination Year-1 (2017.7-2018.6) Median (90% PI)**	**Vaccination Year-2 (2018.7-2019.6) Median (90% PI)**	**Vaccination Year-3 (2019.7-2020.6) Median (90% PI)**	**Total Median (90% PI)**
Gross margin of yellow broiler industry	1091.71	379.16	144.67	1614.31
	(1001.32; 1181.86)	(284.44; 469.27)	(-9.28; 295.92)	(1355.55; 1869.56)
Cost-saving due to human cases avoided	19.13	20.29	22.17	61.59
	(17.58; 21.31)	(18.65; 22.61)	(20.28; 24.71)	(56.60; 68.63)
Cost-saving in poultry outbreak response	3.43	3.53	3.64	10.60
	(1.15; 6.27)	(1.19; 6.45)	(1.22; 6.65)	(3.56; 19.36)
Cost-saving in surveillance in poultry	17.60	9.37	4.98	31.95
	(11.44; 25.22)	(5.75; 14.71)	(1.73; 10.36)	(18.93; 50.28)
Government expenditure on H7N9 vaccines	- 11.25	- 31.12	- 38.51	- 80.88
Expenditure on H7N9 post-vaccination monitoring	- 1.21 (- 0.24; - 2.89)	- 3.75 (- 0.75; - 8.93)	- 5.77 (- 1.16; - 13.76)	- 10.73 (- 2.15; - 25.58)

Change in value compared to pre-vaccination	Vaccination Year-1 (2017.7-2018.6) Median (90% PI)	Vaccination Year-2 (2018.7-2019.6) Median (90% PI)	Vaccination Year-3 (2019.7-2020.6) Median (90% PI)	Total Median (90% PI)
NPV	**1119.17**	**377.68**	**131.03**	**1629.80**
	(1029.36; 1208.86)	**(282.45; 468.38)**	**(- 22.01; 282.46)**	**(1368.13; 1881.85)**
BCR				**18.56 (15.42; 21.75)**

6.3.4 Sensitivity analysis

Yellow broiler wholesale prices contributed 97.7% of the variability of the total NPV of three vaccination years (Figure 6.3), while the inputs of production costs (feed and DoC) shared 1.52% of the contribution to total NPV variance. The inputs of cost-savings in public health and animal health only contributed 0.06% and 0.37% respectively. The inputs of the costs in post-vaccination monitoring accounted for 0.09%, while the yellow broiler wholesale prices accounted for 75.3% of contribution to BCR variance, and inputs of post-vaccination monitoring costs contributed 22.6% of BCR variance (Figure 6.4).

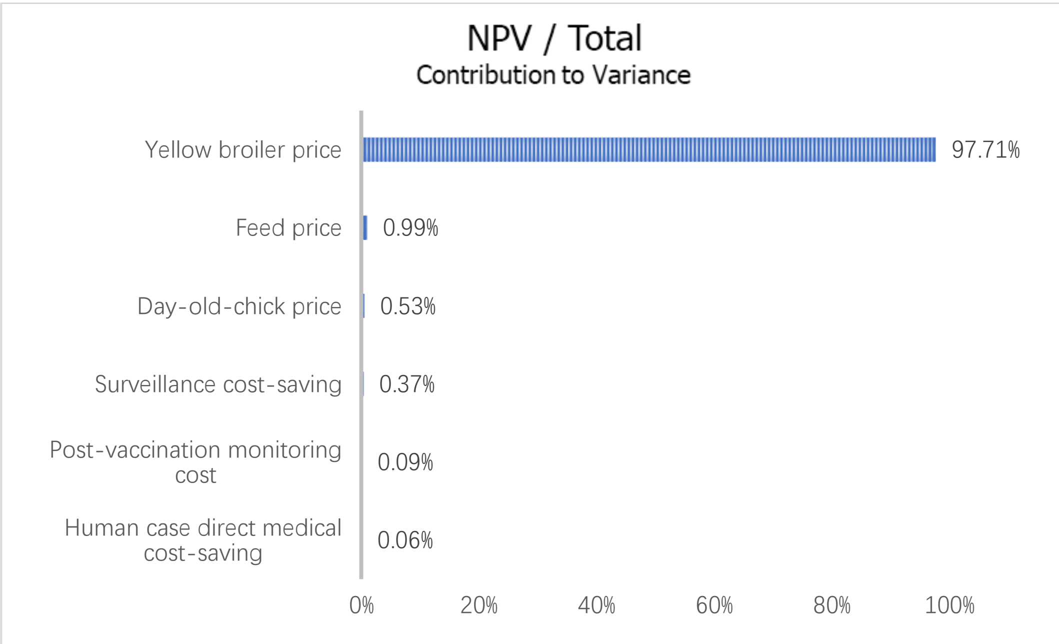


Figure 6.3 Input variables contribution to variance of total NPV in three vaccination years (July 2017-June 2020).

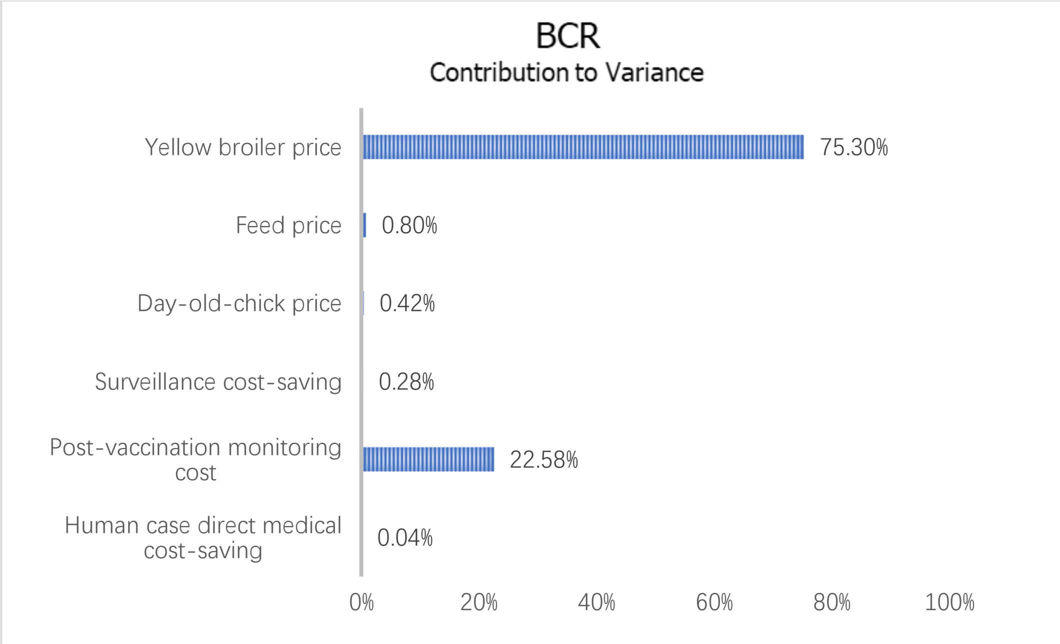


Figure 6.4 Input variables contribution to variance of BCR of three vaccination years (July 2017-June 2020)

6.4 Discussion

This study estimated the economic value of the H7N9 vaccination program in poultry in Guangxi using empirical data. To the best of the authors' knowledge, this is the first study to assess the economic returns of China's H7N9 routine vaccination program. As this study considered both the public health and animal health impacts of the vaccination program and took account of both the private and public sectors, the findings are invaluable in evaluating the current H7N9 vaccination policy, which is critical for implementing actions to achieve better integration with other control measures to mitigate the risk of H7N9 influenza in poultry and humans.

The findings indicated that the current H7N9 vaccination program in Guangxi was economically profitable compared to the absence of the H7N9 vaccination scenario. It is consistent with previous analyses conducted in Asia and Africa that showed that a H5N1 vaccination program provided better economic returns than a no vaccination approach (211, 212). However, the estimated BCR of the H7N9 vaccination program in Guangxi was much higher than a previous analysis of H5N1 vaccination in Nepal (BCR=2.32) (212).

There are several possible explanations for high economic return of H7N9 vaccination in Guangxi. Firstly, a sudden increase of H7N9 human infections in late 2016 and early 2017 in China and the closure of live bird markets (LBMs) as a responsive intervention in many areas resulted in a dramatic decline in the price of yellow broilers, as it is the primary source of live poultry trade in China (29). The number of human infections decreased significantly after launching the H7N9 vaccination in poultry, from about 600 cases nationwide during June 2016 to July 2017 down to four cases from July 2017 to June 2020, with no cases reported in Guangxi (2). It allowed the reopening of LBMs resulting in a rapid rise in the price of yellow broilers (72). Secondly, the substantial production volume of the poultry industry in Guangxi (approximately 2-2.4 billion broilers/year) further amplified the industry benefits. A small increase in gross margin per bird in the yellow broiler industry could result in significant total benefits given the number of birds produced each year. Lastly, the H7N9 vaccination program was integrated into the ongoing H5N1 vaccination program in China, which minimised the incremental cost of the H7N9 vaccination. The H5-H7 combined vaccine replaced the existing H5N1 vaccine and its implementation followed the vaccination protocols and delivery networks used prior to the occurrence of H7N9 in poultry in China (105).

Hence, the additional costs for both growers and government were low, which did not necessarily apply to other countries. These factors could explain the high BCR of H7N9 vaccination in Guangxi. Although the analysis framework only considered benefits to the yellow broiler industry, the BCR of H7N9 vaccination in Guangxi is most likely even higher if benefits for the rest of the poultry industry (less than 15% of total poultry production) were considered.

In this study the economic returns of the H7N9 vaccination program decreased over the three observation years with the greatest economic benefit in the first vaccination year (CNY 1.12billion). A possible explanation for this is a dramatic price rebound occurred in the yellow broiler prices in the first vaccination year due to a significant decrease of human infections after implementation of vaccination with the combined H5-H7 vaccine in poultry. The severe H7N9 epidemics in humans in the winter-spring season of 2016/2017 resulted in the yellow broiler prices dropping from CNY19/bird in August 2016 to their lowest value (CNY11/bird) in early 2017 (2, 154). Following the commencement of H7N9 vaccination in July 2017, the high level of human infections did not occur in the winter-spring season of 2017/2018 as in previous years (129). Subsequently, yellow broiler prices rose steeply (CNY26/bird in November 2017). However, they are likely to reach a new market equilibrium over time; with a gradual decrease in prices after the initial upsurge as evidenced in the most period of three years examined in this analysis (Figure 6.2). It is a likely cause for decreasing economic returns observed in the second and third years of vaccination. Decreasing extra revenue of the yellow broiler industry each year of the vaccination program suggests that the economic incentives for the industry using H7N9 vaccines may decline.

Approximately 94% of the overall benefits of the new vaccination program were directly related to extra revenue of the yellow broiler industry. This supports the rationale of China's H7N9 vaccination program in poultry, where the program was primarily designed to support the poultry industry to recover from the impacts of the severe zoonotic epidemic. In Guangxi, the production of yellow broilers is a critical part of animal production, responsible for about 31% of the GDP generated by livestock/animals (137). If profitability of the yellow broiler industry was low it would directly affect the livelihoods of more than one million Guangxi growers (137), as well as affecting local food security as yellow broilers are one of the important sources of meat (31.9%) for people in Guangxi (37).

The high benefits to the yellow broiler industry in Guangxi (CNY 1.6billion) suggest that the industry would support the new H7N9 vaccination program. This is further supported by the significant drop of the H7N9 prevalence in chickens (by 93%) associated with good vaccination coverage (73%) observed in southern China (157). Given that the industry, in particular the growers, are the primary beneficiaries of the vaccination program it supports the potential for a future private-public-partnership scheme for AI vaccination following a user-pays approach (213). Furthermore, the consequences of previous H7N9 human epidemics to the price of yellow broilers indicates that the opportunity costs of stopping vaccination may be high if H7N9 re-emerged, which could provide strong economic incentives to the growers and industry.

Sensitivity analysis showed the variability of NPV were due mainly to changes in yellow broiler wholesale prices. Yellow broiler prices fluctuated widely during the pre-vaccination and vaccination periods. In contrast, the price of DoC and feed did not change dramatically in the same period. Day-old-chicks and feed can be sold to producers more widely, than the live broilers in areas across different provinces. Therefore, it is rare to observe strong price volatility in these goods as local market influences are smoothed out. Given these factors, it provides a possible explanation that yellow broiler prices primarily contributed to the variance of the H7N9 vaccination program's economic return. An important implication of this finding is that close monitoring of the yellow broiler price would be critical to assess the economic profitability of H7N9 vaccination program in Guangxi. Additionally, the price of yellow broilers may be influenced by the prices of meat from other species such as the dramatic change of pork price linked to African swine fever epidemic (214). Consequently, the gross margin of yellow broilers may not be completely attributable to the effects of vaccination. Hence, an evaluation of the H7N9 vaccination program over a longer time is warranted to consider the economic value of the vaccination policy and to inform future process of vaccination.

The benefits to public health from the H7N9 vaccination program represented only a small proportion (3.6%) of the programs estimated benefits however, this could have been underestimated. The WHO recommends that an economic framework for evaluating direct and indirect costs of a specific disease is based on the number of cases in the area (208). Consequently, the estimated costs of the H7N9 epidemic on public health in Guangxi during the pre-vaccination period was relatively small (CNY 18.6million) given the small number of human cases (n=27) reported in Guangxi. However, reported human cases may be an underestimate of actual infections as not all cases seek health care (215). Unfortunately, the available data from Guangxi did not support the estimation of unreported human cases. Additionally, as one of China's primary broiler production areas, about half of Guangxi's yellow broiler production are exported to other provinces of China (137). These other provinces would benefit from the control of H7N9 in poultry in Guangxi by reducing human infections through live bird trade. The current analysis did not consider possible human infections resulting if H7N9 influenza continuously circulated within the poultry population. In particular, highly pathogenic H7N9 viruses were found both in humans and chickens in early 2017 (17), highlighting the potential impact and amplification of H7N9 on public health if no intervention(s) was undertaken.

There were several limitations in the present study. Firstly, the assumption of the analysis was based on the disease status both in humans and poultry remaining at the same level as that reported in the winter-spring season of 2016/2017 when there was no H7N9 vaccination in poultry. Simulation of the possibility of H7N9 influenza spreading in Guangxi was not included in the study due to the lack of a suitable model. However, the study's assumption would likely be the minimum H7N9 impact scenario if H7N9 viruses keep circulating in poultry and affects humans. The benefits of H7N9 vaccination program compared to not revising AI compulsory vaccination could be higher if on-going epidemics of H7N9 in poultry occurred. Thus, our study at least conducted a minimal estimation of the vaccination program's economic viability, which provides empirical evidence into the discussion of vaccination policies in China. Secondly, the study may not have included all costs arising from the implementation of H7N9 vaccination. Government funding in the research and development of a new H5-H7 vaccine was not considered as there are no data available on this. It may reduce the level of economic returns for the H7N9 vaccination program.

Further analyses to compare the economic impact of H7N9 vaccination and other alternative interventions, such as upgrading biosecurity for poultry farms and LBMs, could be helpful to provide more comprehensive evidence in the policy discussion of H7N9 influenza control. Additionally, longitudinal research to evaluate the benefits and costs of H7N9 vaccination in the longer term when data is available would be more informative for guiding future government policy.

Notwithstanding its limitations, the study clearly demonstrate the significant economic advantage of implementing a vaccination program against H7N9 in Guangxi province, not only for the government but also the yellow broiler industry and the public. The findings offer new evidence to support China's H7N9 vaccination program and debates around economic values of conducting routine AI vaccination in China.

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Chapter 7. General Discussion

7.1 Summary

The findings of the research presented in this thesis provide epidemiological, social, and economic evidence on H7N9 influenza and its control among yellow broilers in southern China's Guangxi province. The yellow broiler production and trading system were investigated and described for the first time in this research, providing evidence to policymakers about the risks and spread of H7N9 through critical pathways. The social and economic aspects of China's H7N9 vaccination program were also evaluated. The findings offer unique insight into the industry stakeholders' practices, attitudes and motivations for using H7N9 vaccines and the economic returns of the H7N9 vaccination program. It is expected that these findings can help improve the risk management of H7N9 and increase the effectiveness of implemented policies. The findings of this research are also likely to be relevant to other provinces in China with similar poultry growing industry models as those in Guangxi, and thus to guide policy formulation for the control and prevention of other emerging AI subtypes.

In Chapter 1, five research objectives were presented with the aim to address the critical gaps in our knowledge of the control of H7N9 influenza. In this final chapter, the findings presented in this thesis will be discussed in relation to these research objectives. For each objective, contributions to existing knowledge and the implications for the control of H7N9 influenza and other emerging AI are also discussed. Later in the discussion, policy recommendations, limitations and future research directions are discussed.

7.2 Contributions to knowledge and implications for H7N9 influenza control

7.2.1 Understanding the yellow broiler production and trading system provides fundamental evidence for the risk management of H7N9 influenza

Previous studies have demonstrated that effective control of animal disease requires a sound understanding of the relevant livestock production and trading system (94, 102-104). However, there has been limited research on how the yellow broiler industry operates in China and its role in transmission of H7N9 AIVs, although they are a primary source of live poultry trade (33). The findings reported in Chapters 3 and 4 presented up-to-date evidence on how yellow broilers are raised, moved, and traded, establishing a complete picture of the populations at risk and transmission pathways for zoonotic H7N9 influenza.

The research revealed that transmission risks for H7N9, along with other AIVs, were high in yellow broilers. Critically, the yellow broiler population had received little attention from government and academia in the control of H7N9 influenza. Previous studies (67, 68, 71) only focused on the role of live chickens in H7N9 risk management and were not able to identify different production and trade characteristics among broiler sectors in China. The characteristics of yellow broiler industry reported in this research (Chapter 3 and 4) indicate that the ways yellow broilers are raised, moved, and traded could facilitate the rapid spread and circulation of AIVs between farms and

LBMs. A large proportion of yellow broiler farms had limited biosecurity management and facilities. This finding may explain why AIVs were often detected in the environments of LBMs throughout China, even in those adopting regular cleaning and disinfection measures (129, 216). The large volume of live broiler movements involving all 111 counties in Guangxi and 24 other provinces (Chapter 4), also highlights that the identified trade networks could lead to the rapid transmission of H7N9 in yellow broilers over a wide geographical area. It confirmed an earlier observation that H7N9 was likely to spread to a wider area through live chicken trade network (67). Additionally, yellow broilers are often raised in an open environment with poor biosecurity facilities and have a relatively long growing period (70 to 150 days). Therefore, they are likely to be at a higher risk of spill over and mutations of AIVs than other types of broilers, especially white broilers who have a shorter growing period of 40 to 45 days. Considering the above-mentioned factors, yellow broilers need to be treated with priority in H7N9 influenza control programs. In particular, the surveillance and vaccination programs need to be more tailored and targeted to yellow broilers.

Several studies (94-97) have indicated that effective animal disease risk management requires a comprehensive understanding of risk pathways covering the whole livestock system. However, in reality, most intervention efforts from the Chinese government have focussed almost entirely on LBMs, with less attention paid to the sources of live poultry trade in the country. There is little published information on how H7N9 AIVs are transmitted between farms and LBMs. The study established that trading platforms play a critical role in the yellow broiler value chain in Guangxi with links to many farms and

LBMs. Trading platforms were also reported as a part of live poultry value chain in other provinces of China (67, 150). However, the training platforms were not included in the national and provincial AI surveillance plans and received little attention from government animal health management (105). Their roles in the risk pathways suggest that monitoring the dynamic trading practices and disease circulation within trade platforms is critical and would enable rapid contact tracing if outbreaks occurred. Additionally, the spatial patterns of live broiler movements reported in Chapter 4 provide critical information on the geographical context, risk pathways, and critical control points along the value chain, which could be used to develop more targeted risk management for H7N9 and other AI in Guangxi.

The research also found that grower companies were the most influential stakeholders, controlling aspects from production to sales and dictating the management practices that farmers should follow (Chapter 3 and 5). It further supports earlier observations in Jiangsu (149) that contract farming can facilitate the implementation of AI control measures. Taken together, engaging the grower companies in the development and implementation of the government H7N9 control program can improve the farmers' compliance to control measures, including vaccination and biosecurity. Meanwhile, the government should provide industry with more ownership and responsibilities in relation to risk management for H7N9 AIVs as the industry is keen to prevent H7N9 influenza to pursue greater profits.

7.2.2 Understanding management practices of stakeholders in yellow broiler industry guides practical interventions

to mitigate H7N9 influenza risks

Understanding risk behaviours can help develop interventions that are better targeted and more practical as human behaviour can play a crucial role in the transmission of many zoonotic diseases, including AI (88, 217-220). However, few studies are available on how the yellow broiler industry stakeholders operate their businesses in China. This research filled the gap and explored stakeholders' management practices and their risky behaviours throughout the whole production and trade process.

Biosecurity needs to be improved, not only in LBMs, but also throughout the whole yellow broiler value chain, particularly the upstream elements of live broiler trading. Some authors believe that LBMs are the most important, if not the only, point of risk in relation to AIVs transmission (12, 60). Hence, the central government of China has been promoting biosecurity improvements in all LBMs in the country (8). However, this research found that, in Guangxi, poor biosecurity existed in various premises from farms to trading platforms, including transport vehicles (Chapter 3). The potential risks posed at these sites have been omitted from the government intervention blueprints, and this could significantly hamper mitigation efforts against the disease.

In addition, the research found that industry stakeholders generally lacked incentives to improve biosecurity (Chapter 3 and 5). The traditional enforcement and penalty-led risk management by the government cannot eliminate all biosecurity risks, furthermore there could be low compliance with government regulations on AI control, as demonstrated in studies in

Guangdong and Chongqing (65, 98). In the commercial sector, actions are driven by profit. If changing practices can bring economic returns, the industry would be more likely to implement them. The government would be in a more favourable position to reduce H7N9 influenza transmission risks by setting standards and procedures for safer broiler products as part of its wider initiative to strengthen biosecurity management.

7.2.3 Identifying critical control points and geographical areas informs a risk-based approach to H7N9 influenza control

The current approach to H7N9 control policies in China, rather than being risk-based, is not targeted. The policies do not consider that the heterogeneity of the broiler population and premises present inherently different levels of risk. Consequently, interventions are implemented in a similar manner in all areas, which results in poor allocation of resources for these interventions and hampers the effectiveness of control of H7N9 if insufficient attention is provided to the riskier sub-populations. The findings of the current research suggest that H7N9 control measures should be targeted to risk, instead of being uniform across the industry.

The research presented in this thesis showed that more than 200 million yellow broilers were produced annually in Guangxi, with the majority of these moved and traded as live chickens through a complex trading network involving different types of premises (Chapter 3 and 4). These findings indicate that the current one-plan-for-all approach could be costly to manage the risks. Through analysing live broiler movements, the majority of movements were found to be associated with a small proportion of exporting and importing counties, with most movements occurring through a small number of high-frequency routes. Those hub counties (either import or export) and high-frequency routes provide evidence on where most central chicken populations in Guangxi are located, and which routes should be targeted to mitigate AIV transmission risks. The simulation presented in Chapter 4 further confirms that targeting areas that play a hub role in live broiler movements would be more efficient to limit the transmission of AI than conducting random interventions. This supports the findings of other studies of other AIVs in different countries of Asia (97, 136, 148).

These findings can be used to improve the current H7N9 surveillance program and to guide the outbreak response and risk management. The areas and routes playing active roles in the movement network require more resources to enable the surveillance system to provide adequate information covering the whole local yellow broiler population and to detect AIVs more quickly. Understanding live broiler movement spatial patterns would make tracing and movement control more effective when outbreaks do occur. These movement patterns can also help to monitor and manage H7N9 influenza introduction risks to Guangxi.

A lack of evidence on critical control points has also made risk-based approaches difficult. Trading platforms and wholesale LBMs were found to be two critical components of the yellow broiler value chain, transitioning a large proportion of live broilers and connecting many farms and retail markets.

Hence, interventions, such as surveillance and upgrade of biosecurity, needs to focus on these premises. This focus would allow government veterinary agencies to achieve the same outcomes more efficiently, with less time and human resources required than the current approach (which requires the inclusion of all premises equally, irrespective of their potential risk).

7.2.4 Understanding of stakeholders' attitudes and motivations on H7N9 vaccination provides new evidence for the AI vaccination policy

The findings reported in this thesis provide unique evidence on industry stakeholders' attitudes and motivations on H7N9 vaccination which was previously unreported. There are different views on whether to continue using vaccination in poultry as a long-term routine AI control measure in China, including H7N9 influenza (129, 160, 161). Some scientists have proposed that mutations of H7N9 AIV or silent infections may occur (166-168). Meanwhile, the prevalence of H7N9 AIVs has remained at a low level with very few human infections cases since the H7N9 vaccination program roll out in China (17, 156, 157, 165).

This research showed that the H7N9 vaccination program was generally well received in the yellow broiler industry in Guangxi. The analysis of the stakeholders' practices, attitudes, and motivations found that most stakeholders believed vaccination was the best tool to control H7N9 AIVs because of its low-cost and easy-to-access features compared with upgrading on-farm biosecurity. There was a strong willingness to continue H7N9 vaccination by the industry, even if the government would no longer provide subsidised or free vaccines in the future. This decision was based on the opinion that emergence of H7N9 human cases would directly cause a huge decrease in broiler prices, with the purpose of vaccination being to reduce the risk of market shocks. The benefit-cost analysis (Chapter 6) further confirmed obvious profit-driven motives by the yellow broiler industry to retain the use of H7N9 vaccines. Decisions around vaccination are seldom free from uncertainty, and sound decision-making requires a wide range of information (170). Social and economic factors need to be considered when policymakers weigh the pros and cons of adopting routine vaccination (162). These findings need to be seriously considered in the debate of whether to continue the current compulsory and free vaccination program. Again, engaging industry stakeholders in the policy process is important.

7.2.5 Assessing the economic viability of the H7N9 vaccination program supports resource optimisation in the control of H7N9

Debates on the H7N9 vaccination program in China have also questioned its economic soundness (169). The economic analysis presented in Chapter 6 provided vital evidence demonstrating that the H7N9 poultry vaccination program in Guangxi province had a good economic return in the first three years of implementation in terms of costs and benefits for the government, the yellow broiler industry, and the general public. This finding contradicts previous economic assessments on routine vaccination against H5N1 in China, which suggested that routine vaccination was less economically viable than the culling without vaccination (169). The earlier study (169) did not include benefits to the poultry industry and to public health in its analysis and mainly focused on public expenditure, and hence was unable to fully evaluate the real economic viability of routine vaccination against AI in China.

The primary beneficiary of the current H7N9 poultry vaccination program was the yellow broiler industry, as increased gross margins comprised about 95% of the additional benefits (Chapter 6). Additionally, the yellow broiler industry expressed their willingness to pay for H5-H7 vaccination, and some producers had already been purchasing H5-H7 vaccines from the market even while vaccines were provided free by the government (Chapter 5). These findings suggest it is possible to apply the beneficiary pays principle, in which the industry should contribute more to the costs of H7N9 vaccination to save public expenditure. The government could try to focus on smallholders who are financially less resilient than large grower companies. This could result in significant savings, more than CNY 100 million each year, in public expenditure on vaccination which could then be redirected to more needy areas such as improving biosecurity infrastructure and surveillance.

7.3 Recommendations to policymakers on the prevention and control of H7N9 influenza in China

Based on the research findings, the following recommendations are made for improving H7N9 influenza control and related risk management in China. These recommendations were provided in Chinese to the Guangxi and Chinese national veterinary authorities to guide the control of H7N9 influenza and other types of emerging zoonotic diseases.

1. Tailor H7N9 influenza control strategies to different industry production and trading features.

In China, the yellow broiler industry has a different production and trading system than the white broiler industry. The unique features of the yellow broiler industry expose them to a higher chance of being infected by H7N9 AIVs and then maintaining and spreading these viruses. Therefore, the study suggests that policymakers examine the complete value chains of different types of broilers, thus allowing more targeted and effective risk management of H7N9 and other AIVs. As key tools to mitigate the risks of H7N9 influenza, surveillance and vaccination should be tailored to different risk levels in the poultry population and their respective risk pathways.

2. Promote and adopt risk-based approaches in H7N9 influenza control

This research demonstrated that risk-based approaches, built on understanding yellow broiler production and trade characteristics, were more effective than a single plan for interventions in Guangxi irrespective of the industry differences or risks of transmission. A thorough study on live poultry value chains and movement patterns could provide reliable evidence on the H7N9 transmission risks and thus serves as the basis of intervention planning. It would also allow implementers to achieve the best result with limited resources. Therefore, it is suggested that the veterinary authorities support or conduct research for more comprehensive and up-to-date epidemiological evidence on value chain and movements patterns.

3. **Enhance public-private partnerships (PPP) in H7N9 influenza control programs through policy consultation and creating ownership in risk management.**

Public-private partnerships in the yellow broiler industry are generally found between grower companies and local veterinary authorities. The study found that grower companies were most influential among industry stakeholders due to their large share of the market and the way they work with farmers. Thus, it is important to engage grower companies in H7N9 risk management. The government's aim to mitigate disease risks can be best achieved through harnessing the potential of the most influential industry stakeholders. Since the study found that the industry has a strong willingness to invest in AI control measures, including vaccination in poultry, it makes sense that the grower companies would pay for the vaccination, while the government only focuses on supporting smallholders who are less resilient in the face of poultry disease outbreaks (221).

4. **Improve biosecurity throughout the live broiler trade value chain, in particular the elements upstream of live bird markets.**

This research found that lack of incentives for industry stakeholders to improve farm biosecurity has reduced the effectiveness of government efforts for H7N9 influenza control. Government has acknowledged that poor biosecurity has existed in LBMs. However, other critical points of risk in the trade chain have not received enough attention, including farms and premises linking farms and LBMs. Successful government policies would help industry turn their biosecurity investment into profits and thus improve the overall environment.

5. **Research on social and economic aspects in relation to H7N9 should be conducted to further understand the risks and provide multi-dimensional evidence for control policies.**

Social and economic factors have a large impact on the uptake of proposed disease interventions (30, 220). A well-designed H7N9 control strategy requires an integrated approach considering biological, epidemiological, social, and economic aspects to attain a desired level of effectiveness. As most previous research has focused on the biological aspects of H7N9, the government needs to support more interdisciplinary and multidisciplinary research to enrich the understanding of social and economic aspects of the disease.

6. **Conduct a study to assess the potential impact of ceasing compulsory H7N9 vaccination and develop a set of criteria for future AI vaccination cessation.**

As there have been ongoing debates on whether to stop compulsory AI vaccination (129, 160, 161, 169, 176, 177), it is logical to conduct a study to examine all aspects of this issue. The research presented in this thesis revealed some industry stakeholders would support the phase-out of the current compulsory H7N9 vaccination program. However, considering the size of the poultry population in China and its role in the country's agriculture and livelihood, major policy changes of this kind require more evidence before the final decision.

7.4 Limitations

Several limitations to this research need to be noted when interpreting the findings arising from the current research. Firstly, the studies presented in this thesis were cross-sectional studies that were conducted at a specific point in time. Hence, it is not possible to capture potential changes in the yellow broiler industry and the stakeholders' practices and attitudes over time. Up-to-date evidence is needed for understanding the risks of H7N9 transmission. Secondly, this research focused on Guangxi province; thus, the findings may not reflect H7N9 in other provinces in China. Different areas of China differ in their social and cultural contexts, and their chicken meat consumption preference also varies (107). These may lead to different broiler production and trade systems, as well as different perceptions and attitudes of stakeholders. Using the methods presented, further research could be undertaken to investigate stakeholders' opinions in different regions. Thirdly, this research did not investigate Chinese consumers' attitudes on H7N9 vaccination in poultry as there were insufficient resources available. Consumers' perception or misconception about vaccination may determine their choices of product and thus encourage or discourage the growers to change practices adopted.

7.5 Areas for future research

To expand on the research presented in this thesis it is recommended that future research include:

- Pilot studies to assess the possible epidemiological, social and economic impacts of the withdrawal of H7N9 vaccination program in China

- Longitudinal studies to monitor possible changes in the yellow broiler industry and provide up-to-date understanding of the H7N9 transmission risks along the value chain

- Research covering more areas of China to enrich the understanding of diversity in the poultry industry and the different social and economic factors relating to the control of H7N9

- Qualitative and quantitative risk analysis based on the finding of the value chain study would provide comprehensive evidence for the H7N9 risk management.

- Studies to better understand consumers' attitudes on different interventions in the H7N9 influenza control program, particularly vaccination in poultry and reducing live broiler supply.

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Appendix A. Supplementary Materials of Chapter 3

A.1 Supplementary Material 1. Semi-structure interview questions

1. Stakeholders in the production phase

1) Basic situation

- Please briefly describe your farm/company (e.g. number of broilers, number of farms).
- Please tell us about your infrastructure/facilities.
- Please tell us about your breeds and production cycle.
- Please tell us your management/business model of your farm/company.
- What are the costs of production? How much of each? (or proportion)
- What are the incomes/revenue for your farm/company? What is your opinion on your profits?
- How many staff work on your farm/company? How do you manage them? Any other human resources you used? What? And why you need those support?

2) Practices

- Please describe your daily operation.
- Please describe your production operation (e.g. feeding, vaccination)
- Please tell us about how you manage farm biosecurity. Any facilities?
- How do you handle the sick birds? How do you handle the dead birds?

- What are the major concerns in your practices?
- What are your concerns on animal health issues in your production?

3) Interactions

- Types of inputs for your farm/company? Source of these? (e.g. DoC, feeds, drug, vaccine) How do you work with them?
- Types of outputs for your farm/company? Source of these? (e.g. dead bird, manure) How do you work with them?
- Please describe your sales. (e.g. Who? When? Where?) How do you manage your sales?
- Any others work with you? How?
- What are your interactions with local veterinary officials?

4) Rules/norms

- What are the challenges you face in your business?
- Who are influential stakeholders in your business? Why and how?
- How long do you work in the yellow broiler industry?
- Any rules or standard from the industry? What are they? How do they work?
- What are the challenges the yellow broiler industry face?
- What is your opinion on yellow broiler industry development? (e.g. opportunities, constraints)
- What government regulation/rules to your business? How does it work?
- What is your opinion on the market price of yellow broiler in the past twelve months? What about the market situation in the past three years?

- Does avian influenza affect your business? How? And how do you cope with?
- What is your opinion on avian influenza control? Any challenges? Any suggestions on the current avian influenza control program?

2. Stakeholders in the trading phase

1) Basic situation

- Please briefly describe your business
- Please tell us about your infrastructure/facilities/setting
- What are the incomes/revenue for your business? What is your opinion on your profits?
- What are the costs in your business? How much of each? (or proportion)
- How many staff work in your business? How do you manage them? Any other human resources you used? What? And why you need those support?

2) Practices

- Please describe your trade operation (e.g. feeding, vaccination)
- Please describe the market operation.
- How do you manage clean and disinfection in your stall/area?
- How do you handle the sick birds? How do you handle the dead birds?
- What are the major concerns in your practices?

3) Interactions

- Please describe your sales. (e.g. Who? When? Where?) How do you manage your sales?
- Where do you buy broilers? From whom? How often? How do you work with them?
- Who are the people buy broilers from you? Where are they based? How often? How do you work with them?
- Any other types of inputs for your business? (e.g. feeds) Source of these? How do you work with them?
- Any others work with you? How does it work?
- What are your interactions with local veterinary officials?
- What are your interactions with other stalls in the same market?

4) Rules/norms

- What are the challenges you face in your business?
- Who are influential stakeholders in your business? Why and how?
- How long do you work in the yellow broiler industry?
- Any rules or standard from the industry? What are they? How do they work?
- What are the challenges the yellow broiler industry face?
- What is your opinion on yellow broiler industry development? (e.g. opportunities, constraints)
- What government regulation/rules to your business? How does it work?
- What is your opinion on the market price of yellow broiler in the past twelve

months? What about the market situation in the past three years?

- Does avian influenza affect your business? How? And how do you cope with?
- What is your opinion on avian influenza control? Any challenges? Any suggestions on the current avian influenza control program?

3. Veterinary Officials

1) Basic situation

- Please briefly describe yellow broiler production in your area.
- Please tell us about the farm infrastructure/facilities in your area.
- Please tell us about the production business model in your area.
- Please tell us about how yellow broilers were traded in your area.
- Please briefly describe how LBMs operate in your area.
- What is your opinion on the market price of yellow broiler in the past twelve months in your area? What about the market situation in the past three years?

2) Practices

- Please describe your daily work in relation to yellow broiler production and trading, and avian influenza control.
- How many staff involved in these works? How do you manage them? Any other human resources you used? What? And why you need those support?

- How do you think on-farm biosecurity management in your area?
- How do you think LBMs biosecurity management in your area?
- Any gaps in stakeholder practices which may pose the risk of avian influenza transmission?

3) Interactions

- What are your interactions with local stakeholders in yellow broiler production and trade?
- How do you work with other levels of veterinary agency in avian influenza control and prevention?

4) Rules/norms

- What are the challenges you face in your work with yellow broiler industry?
- What government regulation/rules related to yellow broiler production and trading? How do they work?
- Who are influential stakeholders in yellow broiler industry? Why and how?
- Any rules or standard from industry? What are they? How do they work?
- What are the challenges the yellow broiler industry face?
- What is your opinion on yellow broiler industry development? (e.g. opportunities, constraints)
- What is your opinion on avian influenza control? Any challenges? Any suggestions on the current avian influenza control program?

A.2 Supplementary material 2. Checklists of on-site observation

1. Farm

- Shed setting
- Facilities in shed
- Water facilities
- Feeding facilities
- Clean and disinfection infrastructure/facilities
- Storage facilities and location
- Disposal area and location
- Living area location
- Management of visitors
- Management of vehicles
- Personnel protection equipment

2. Trading platform

- Platform infrastructure and setting
- Facilities in the platform
- Clean and disinfection infrastructure/facilities
- Loading area setting
- Entrance and path
- Management of visitors

- Management of vehicles
- Personnel protection equipment
- Trade operations

3. LBMs

- Market infrastructure and setting
- Facilities in the market
- Stall infrastructure and setting
- Clean and disinfection infrastructure/facilities
- Loading area setting
- Entrance and path
- Management of vehicles
- Personnel protection equipment
- Trade operations
- Slaughtering service infrastructure, facilities and operation

Appendix B. Supplementary Materials of Chapter 4

B.1 Supplementary Tables

Table B. 1 Broiler movements from Guangxi counties, 2017

	To other provinces	Within Guangxi
Number of movements (%)	51,481 (30.9)	115,210 (69.1)
Number of broilers moved (%)	98,167,142 (49.3)	100,933,894 (50.7)
Number of broilers/movement median (IQR) [min - max]	1,700 (1,000-2,649) [1-40,000]	564 (250-1,100) [1-36,000]
Number of edges (%)	1,664 (52.1)	1,531 (47.9)
Number of movements/edge median (IQR) [min - max]	3 (1-12) [1-2,084]	5 (2-24) [1-11,167]
Number of broilers/edge median (IQR) [min - max]	6,000 (2,440 – 23,522) [4 - 3,617,628]	5,540 (1,600 – 27,200) [10 - 4,653,222]

Table B. 2 Summary of the monthly frequency of movements from Guangxi to other provinces in China in 2017

Number of months that edge had a movement	Number of edges (%)	Number of movements (%)	Number of broilers moved (%)
1-3	1,122 (67.4)	3,075 (6.0)	7,046,065 (7.2)
4-6	227 (13.7)	3,077 (5.9)	5,939,380 (6.0)
7-9	126 (7.5)	3,895 (7.5)	7,683,851 (7.9)
10-12	189 (11.4)	41,434 (80.6)	77,497,846 (78.9)
Total	1,664	51,481	98,167,142

Table B. 3 Summary of nodes centrality in yearly network of intra-provincial movements of Guangxi in 2017

Parameter of node centrality	Median (IQR) [min - max]
In-degree	10 (6 - 20) [1 - 59]
Out-degree	7 (1 - 21) [0 - 60]
In-strength	390 (83 – 838) [5 – 23,738]
Out-strength	44 (2- 467) [0 – 19,309]
Betweenness	86.55 (2.31 - 313.77) [0 - 1968.18]

Table B. 4 Summary of the monthly frequency of movements of broilers between counties within Guangxi in 2017

Number of months that edge had a movement	Number of edges (%)	Number of movements (%)	Number of broilers moved (%)
1-3	881 (57.5)	2,735 (2.4)	3,638,756 (3.7)
4-6	225 (14.7)	3,848 (3.3)	4,379,993 (4.3)
7-9	145 (9.5)	5,581 (4.8)	5,220,148 (5.2)
10-12	280 (18.3)	103,046 (89.5)	87,694,997 (86.8)
Total	1,531	115,210	100,933,894

B.2 Supplementary Figures

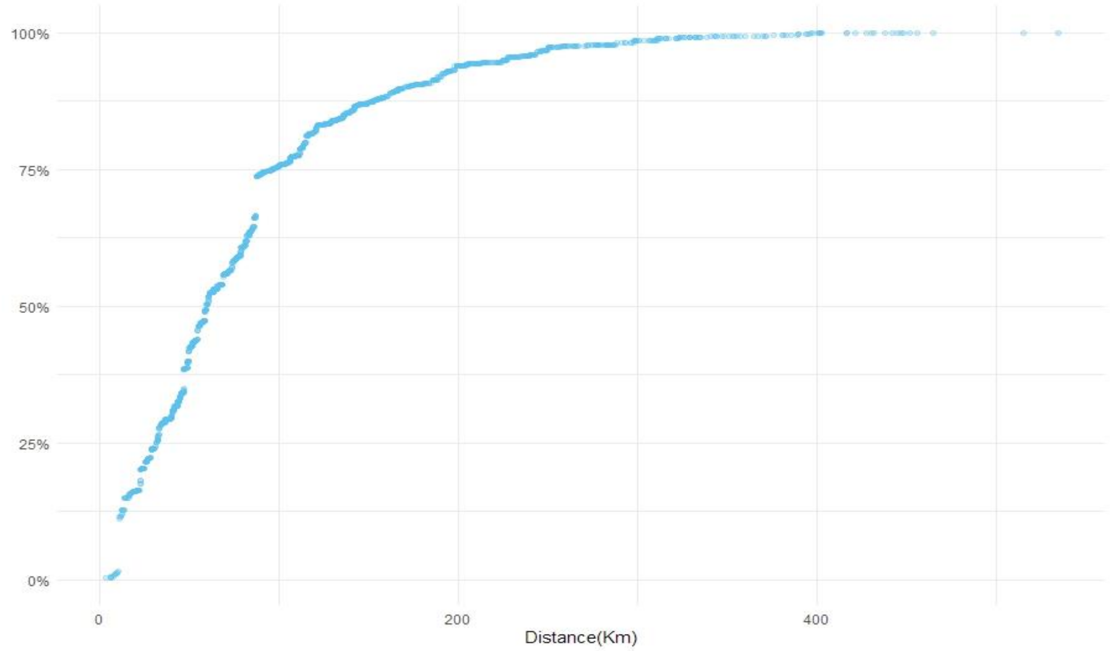

Figure B. 1 Cumulative distribution of movements within Guangxi in 2017 as a function of their Euclidian distance

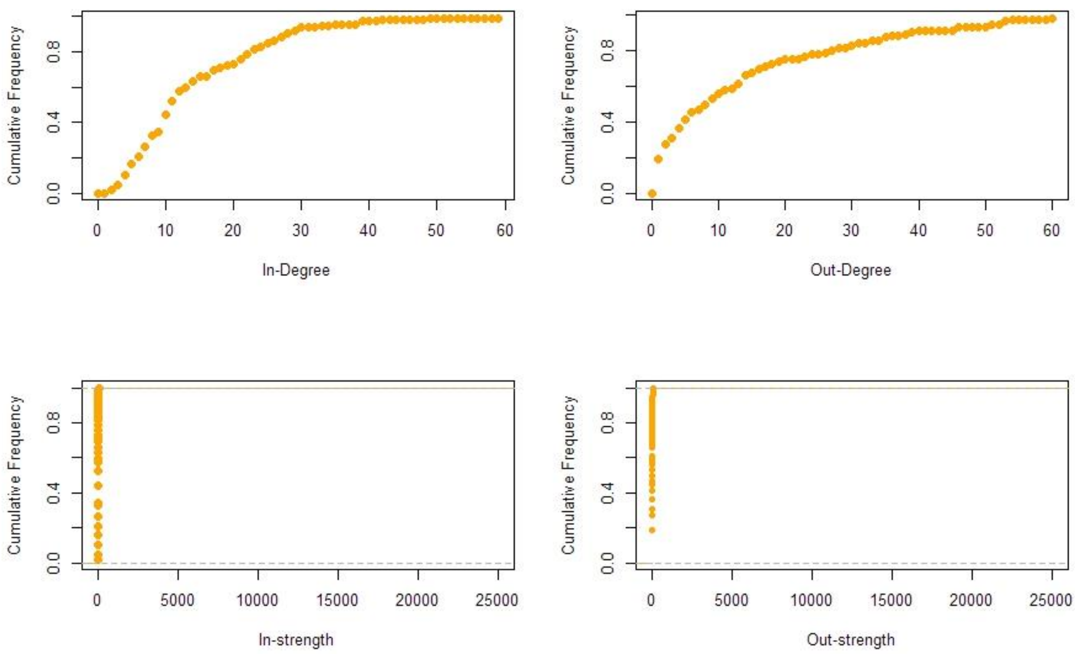

Figure B. 2 Distributions of in- and out-degree (upper two) and in- and out-strength (lower two) of all counties in intra-provincial broiler movement network of Guangxi, 2017.

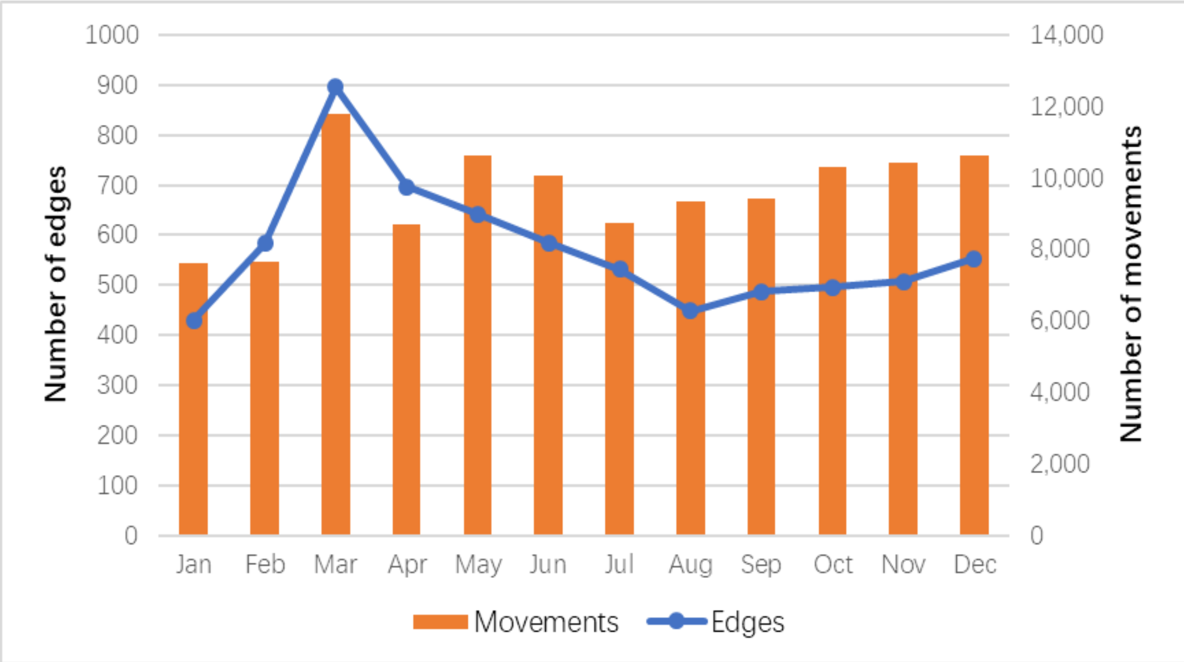

Figure B. 3 The number of movements and edges between counties in Guangxi, in the months of 2017

Appendix C. Supplementary Materials of Chapter 5

C.1 Supplementary Tables

Table C. 1 Socio-demographic characteristics of the participating yellow broiler farms and village para-veterinarians (Para-vets) for the online questionnaire survey in Guangxi, from May to July 2019.

Variables	Farmers (n=118)		Para-vets (n=34)	
	n	%	n	%
Age of farmer (years)				
≤30	16	13.6	5	14.7
31-40	62	52.5	10	29.4
>40	40	33.9	19	55.9
Education (years)				
≤9	66	55.9	7	20.6
>9	52	44.1	27	79.4
Duration of involvement with the yellow broiler industry (years)				
<3	20	16.9	4	11.8
3-10	61	51.7	13	38.2
>10	37	31.4	17	50.0
Batch size (birds)				
≤10,000	64	54.2	NA	
>10,000	54	45.8	NA	
Slaughter-age of bird raised (days)				
60-80	14	11.9	NA	
81-110	30	25.4	NA	
>110	74	62.7	NA	
Have a yellow broiler farm				
Yes	NA		10	29.4
No	NA		24	70.6
Operation mode				
Contract-farm	112	94.9	4	40
Independent farm	6	5.1	6	60

Table C. 2 Brief description of interviewees for individual interviews in Guangxi in July 2019 (n=36)

	Wuming	Xingye
Farmers (n=11)	6 (2 Female, 4 Male) Operation mode: • Contract farmer: 5 • Independent farmer: 1 Farm size: • ≤10,000chicken/batch: 5 • >10,000 chicken/batch:1	5 (Male) Operation mode: • Contract farmer: 4 • Independent farmer: 1 Farm size: • ≤10,000 chicken/batch: 2 • >10,000 chicken/batch: 3
Managers of grower companies (n= 16)	6 (Male) Number of farms: • <500: 4 • 500-1000: 2	10 (1 Female, 9 Male) Number of farms • <500: 1 • 500-1,000: 7 • >1,000: 2
Para-veterinarians (n=4)	2 (Male) Years of experience: • ≤10 years: 1 • >10 years:1	2 (Male) Years of experience: • >10 years:2
Government veterinarians of county-level CADCs (n=5)	2 (Female) Years of experience: • ≤10 years: 1 • >10 years:1	3 (1 Female, 2 Male) Years of experience: • ≤10 years: 2 • >10 years:1

C.2 Supplementary Material 1. Online questionnaires used in the study

Questionnaire A (Participants: Farmers)

1. Average batch size of broiler raised (birds)
   A. < 5000
   B. 5000-7999
   C. 8000-10000
   D. >10000
2. Slaughter-age of bird raised (days)
   A. <60
   B. 60-80
   C. 81-110
   D. >110
3. Number of batches raised in a year？
   A. <2.5
   B. 2.5 - 4
   C. >4
4. Operation mode of the farm
   A. Contract farm
   B. Independent farm
   C. Others, please specify:________
5. Do you agree that control H7N9 is priority for your farm ？
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
6. Do you agree that control H5 is priority for your farm?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
7. Do you agree that control H9 is priority for your farm?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree

E. Strongly disagree

8. Do you concern about avian influenza affect your health?
   A. Always
   B. Usually
   C. Sometimes
   D. Rarely
   E. Never
9. Do you agree that vaccination is best approach to control avian influenza?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
10. What is the source of the H5-H7 bivalent vaccine you used?
    A. Government-provided vaccine
    B. Commercial vaccine
    C. Both Government-provided and Commercial vaccine
    D. Don't know the source
    E. Autogenous vaccine
    F. I don't use the vaccine
11. How many injections of H5-H7 bivalent vaccine your chicken take?
    A. 0
    B. 1
    C. 2
    D. 3
    E. I don't know
12. What is the most important factor you would consider if you choose the AI vaccine?
    A. Vaccine effectiveness
    B. Vaccine side effects
    C. Vaccine price
    D. Number of doses
    E. Follow other farmers' choice
13. What do you think the quality of government-provided H5-H7 bivalent vaccine?
    A. Very high quality
    B. High quality
    C. Neither high nor low quality
    D. Low quality
    E. Very Low quality
    F. Not sure

G. No comment as never used

14. If AI outbreak occurs, which source vaccine you prefer to use?
    A. Government-provided vaccine
    B. Commercial vaccine
    C. Both Government-provided and Commercial vaccine
    D. Don’t know the source
    E. Autogenous vaccine
    F. I don’t use the vaccine
15. If government stop to provide free H5-H7 bivalent vaccine, would you continue to use the vaccine?
    A. Very likely
    B. Likely
    C. Neither likely nor unlikely
    D. Unlikely
    E. Very unlikely
    F. Not sure
    G. I will follow the instruction from my partnering company

16. Your age: ______
17. Years of education: ________
18. Duration of involvement with the yellow broiler industry (years) ____________

Questionnaire B (Participants: Para-veterinarian)

1. Do you agree that control H7N9 is priority for farmers in your area?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
2. Do you agree that control H5 is priority for farmers in your area?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
3. Do you agree that control H9 is priority for your farm in your area?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
4. Do you concern about avian influenza affect to farmers' health?
   A. Always
   B. Usually
   C. Sometimes
   D. Rarely
   E. Never
5. Do you agree that vaccination is best approach to control avian influenza?
   A. Strongly agree
   B. Agree
   C. Neither agree nor disagree
   D. Disagree
   E. Strongly disagree
6. Do you think what the most important factor farmers would consider when choosing the AI vaccine?
   A. Vaccine effectiveness
   B. Vaccine side effects
   C. Vaccine price
   D. Number of doses
   E. Follow other farmers' choice
7. What do you think the quality of government-provided H5-H7 bivalent vaccine?
   A. Very high quality

B. High quality
C. Neither high nor low quality
D. Low quality
E. Very Low quality
F. Not sure

8. If government stop to provide free H5-H7 bivalent vaccine, do you think farmers you continue to use the vaccine?
   A. Very likely
   B. Likely
   C. Neither likely nor unlikely
   D. Unlikely
   E. Very unlikely
   F. Not sure
9. Your age: ______
10. Years of education: ________
11. Duration of involvement with the yellow broiler industry/work as para-vets (years) ___________
12. Do you have yellow broiler farm?
    A. Yes (Jump to Q 13)
    B. No (End of questionnaire)
13. Operation mode of your farm
    A. Contract farm
    B. Independent farm
    C. Others, please specify:_______

C.3 Supplementary Material 2. Semi-structure interview open-ended questions

A. Participants: Farmers and grower company managers

Q1. Please briefly describe your farm/company
e.g. number of broilers/number of farms, your breeds, production cycle and farm management

Q2. What are the costs of production? How much of each (or proportion)? How about your revenue and profit?

Q3. What are the most concerns in your production management? Why?

Q4. What are the prioritised diseases to be control/prevent in your farm? Why?

Q5. How much do you agree that H7N9 prioritised diseases to be control/prevent in your farm? Why? How about H5? Why?

Q6. Please briefly describe how you manage the vaccination in your farm/company? And what is your protocol on AI vaccination (e.g. schedule, vaccine source)?

Q7. What is your opinion on using vaccine to control AIVs?

Q8. What are your motives to use vaccine to control H7N9? And how about H5?

Q9. What is your opinion on current compulsory AI vaccination program? Any suggestions?

Q10. What are the factors you would like to focus for choosing AI vaccine? Why?

Q11. How do you think government-provided vaccine? Any advantages or disadvantages?

Q12. If government stop providing free AI vaccine, would you like to continue the vaccination? Why?

B. Participants: Para-veterinarians and official veterinarians

Q1. Please briefly describe yellow broiler production situation in your area e.g. number of broilers/number of farms, your breeds, production cycle and farm management

Q2. What are farmers' primary concerns in the production management? Why?

Q3. What are the prioritised diseases to be control/prevent in the yellow broiler farm? Why?

Q4. How much do you agree that H7N9 prioritised diseases to be control/prevent in the yellow broiler farm? Why? How about H5? Why?

Q5. Please briefly describe how farmers manage the vaccination in your area? And what are their protocol on AI vaccination (e.g. schedule, vaccine source)?

Q6. What is your opinion on using vaccine to control AIVs?

Q7. What are farmers' motives to use vaccine to control H7N9? And how about H5?

Q8. What is your opinion on current compulsory AI vaccination program? Any suggestions?

Q9. How do you think government-provided vaccine? Any advantages or disadvantages?

Q10. If government stop providing free AI vaccine, how much do you agree that farmers/growers would like to continue the vaccination? Why?