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African swine fever in China: Impacts, responses, and policy implications

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ABSTRACT

African Swine Fever broke out in China in August 2018 and has caused a substantial loss to China's hog industry. Pork is the dominant meat in the Chinese diet with its price being a critical component of China's Consumer Price Index. In 2019, large increases in the pork price caused by the sharp reduction in pork supply incentivized the government to suppress the price by subsidizing large-scale hog farms. With an updated estimation of China's meat demand, we argue that the ongoing policy interventions may not be the most efficient for achieving short-run reductions in the pork price. Subsidizing the production of chicken, a major substitute for pork and currently accounting for a relatively small share of meat consumption in China, could help suppress the pork price faster and at lower government costs. We estimate price dynamics and compute consumer surplus of multiple subsidy plans over a 30-month window from the third quarter of 2019 to the last quarter of 2021. Simulation outcomes suggest that allocating some subsidies from hog to chicken farms is likely to benefit consumers, producers, and the government. Our novel proposal of expanding production of a substitute meat to help lower the pork price after a large loss of the hog stock may be useful to other countries that suffer or may suffer from severe livestock losses due to animal epidemics.

1. Introduction

China, the world's largest producer and consumer of pork, reported the first case of African Swine Fever (ASF), a highly contagious and deadly viral disease of hogs, in one of its Northeastern provinces on August 3, 2018 (USDA, 2019a). Within eight months, the disease spread to all of China's mainland provinces and caused a substantial loss to its hog industry (USDA, 2019b). China's Ministry of Agriculture and Rural Affairs reports that the stock of hogs decreased from 320.8 million to 190.9 million by August 2019, a loss of 40.5%, while the stock of sows fell from 31.3 million to 19.0 million, or 39.3%.

It did not take long for the loss of hogs to translate into a drop in the pork supply. Annual domestic pork production in 2019 fell by 21% from its 2018 level, which was reflected by the rapidly increasing wholesale and retail prices of pork in the second half of 2019. The real-RMB wholesale price more than doubled the pre-ASF level by November 2019, reaching a historical record of 51 RMB per kilogram. In the meantime, the retail price climbed all the way up from 25 to over 60 RMB per kilogram.

With pork being the dominant meat in the Chinese diet, the sharp price increase made headlines on major news media and pressured the Chinese government to keep pork prices down to a "reasonable range", especially when the Chinese New Year, the peak demand season, approached in late 2019.[1] Both the central and provincial governments, instead of subsidizing individual consumers, have announced and implemented a series of policies aimed at fully recovering domestic hog and pork production within a 2–3 year window.

China's domestic supply of pork may not recover so quickly due to the long biological cycle of hog production. With ten months needed from an embryo to a finished hog, even in an ideal situation where ASF were extinguished and millions of piglets were immediately added to the stock, the supply of pork might not be anywhere near the pre-ASF level until the end of 2020. In reality, the disease remains far from being eliminated,[2] and achieving such a large piglet supply is unlikely given a two-fifths reduction in the domestic stock of sows. To help increase the supply of pork, China also increased pork imports during 2019 by nearly

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[1] News articles available in Chinese at: http://www.gov.cn/premier/2019–11/07/content_5449896.htm; http://www.gov.cn/xinwen/2019–11/09/content_5450485.htm.

[2] Real-time ASF cases are reported by the China's Ministry of Agriculture: http://www.moa.gov.cn/gk/yjgl_1/yqfb/.

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70% from 2018 and released frozen pork in stockpiles. Imported and stockpiled pork, however, is far from making up the domestic supply loss, because it accounts for less than 5% of pre-ASF domestic production.

Our research focuses on another strategy that has the potential to help China suppress the pork price in the short-run: subsidizing farms that supply ASF-resistant substitute meats with shorter production cycles. Specifically, prior studies suggest that chicken may be the ideal candidate. So far, chicken only accounts for 12–13% of meat consumption in China, which is less than a half of the pork share. This share is much lower than the world average of 41%, than the 44% of most western countries, and even that of other Asian countries with similar food cultures.[3] There seems to be considerable room for China to expand its chicken consumption.

To examine China's meat markets under alternative subsidy policies, we collect data on Chinese meat consumption and prices, including pork, beef, mutton, poultry, and aquatic meats from 1991 to 2018. The data are used to estimate the own-quantity flexibility (i.e., percent change in price of a good over one percent increase in quantity supplied in the market) and cross-quantity flexibilities of pork against other meats. The first-differenced Inverse Almost Ideal Demand System (IAIDS) model is employed over the commonly used AIDS model because of its enhanced ability to characterize demand for perishable commodities like fresh meats (Eales and Unnevehr, 1993; Eales and Unnevehr, 1994). We allow for structural breaks during the three-decade period based on the Maximum Likelihood Estimation (Moschini and Meilke, 1989). Estimation shows that chicken is a substitute for pork.

Using the estimated quantity flexibilities, we characterize a simulation model to evaluate price effects of alternative subsidy policies. We estimate the total subsidies needed to increase the output of pork and/or chicken for target price reductions set by the government. With a few assumptions, we compare simulated price dynamics under various subsidy allocations to hog and chicken farms from the third quarter of 2019 to the end of 2021. Subsidizing chicken farms, in addition to subsidizing hog farms, tends to lower pork prices two quarters earlier, increase consumer surplus, and reduce government expenditure considerably.

Our study mainly makes two contributions to the literature. First, we model China's meat demand in the recent three decades and provide updated estimates of price-quantity relationships for four major meats. We allow for a structural change, giving our estimation another advantage over prior estimations (e.g., Gould and Villarreal, 2006; Liu et al., 2009; Ortega et al., 2009a). Second, we contribute one of the first policy discussions on the recovery of the world's largest hog industry after the heavy hit by ASF, which has significant influences on China's livestock sector as well as international markets of meats, soybean, and other feed grains (Wu, 2019; Zhang et al., 2019; Mason-D'Croz et al., 2020). To our knowledge, economic research on price and production changes during the recovery from animal epidemics has been scant. Our novel proposal of expanding production of a substitute meat to help lower pork prices after a substantial loss of the hog stock in China may benefit other countries that suffer or may suffer from severe livestock loss due to animal epidemics like ASF.

2. Supply shock and alternative policy responses

In this section, we first discuss the impacts of ASF on China's hog stocks and pork prices. We then summarize the Chinese government's announced and ongoing policies that aim to suppress pork prices and help recover pork supply based on a survey of news reports and discuss the limitation of these policies. Finally, we propose an alternative policy response relying on the economic literature and highlight its advantages to bringing down pork prices within a relatively short period of time.

[3] Meat consumption data reported by OECD: https://data.oecd.org/agroutput/meat-consumption.htm

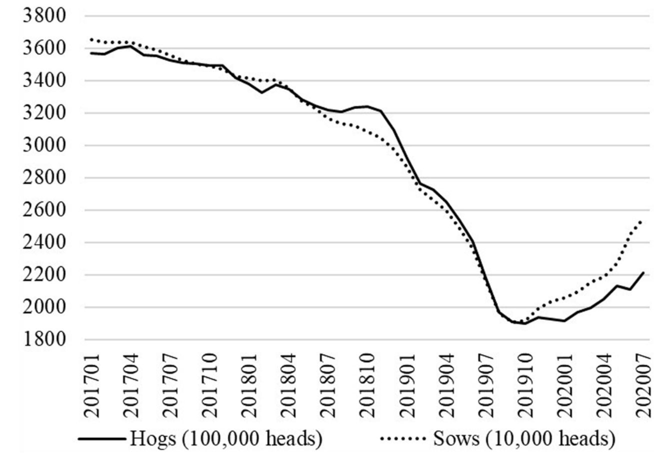

Fig. 1. Monthly stock of pigs and sows in China. Source: Ministry of Agriculture and Rural Affairs of China. Notes: The horizontal axis indicates year and month. For example, 202,007 refers to the 7th month of 2020, namely, July 2020.

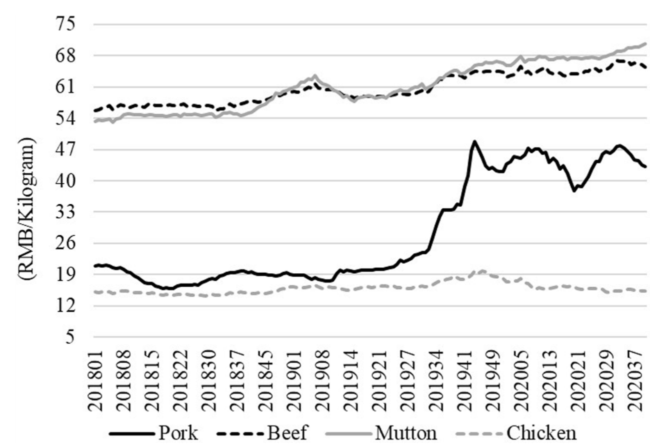

Fig. 2. Nation-level weekly wholesale prices of meats in China. Source: http://www.zhujiage.com.cn and http://pfsc.agri.cn/fxbgzb/. Notes: Data cover the first week of 2018 to the last week of September 2020. Real prices are reported with January 2018 as the baseline. The original data of hog prices are at province level. The simple nation-level average prices are computed, excluding data of Hainan, Ningxia, Qinghai, and Xizang Provinces due to missing observations. The horizontal axis indicates year and week. For example, 202,037 refers to the 37th week of 2020.

2.1. Declining hog stocks and rising prices

ASF heavily struck China's hog industry from August 2018 to October 2019. Fig. 1 shows that the stocks of hogs and sows had been slowly declining from early 2017 to mid-2018, perhaps due to environmental restrictions on hog farms (Gu and Josephine, 2017). After the outbreak of ASF, the month-end inventory of hogs and sows both experienced sharp and rapid falls. By December 2019, the stocks of sows and hogs were only 64% and 60% of the pre-ASF level, respectively. Not surprisingly, the production of pork in 2019 declined by 21.3% compared with 2018. Both stocks were slowly restored in 2020. By July 2020, the stocks of sows and hogs reached 80% and 68% of the pre-ASF level, respectively.

Wholesale and retail prices of pork started to rise in mid-2019 and quickly broke their historical records after doubling the pre-ASF levels. Fig. 2 shows real-RMB weekly national-average wholesale prices of pork

Table 1
Supporting policies on hog production after the African Swine Fever.

Date of news released	Provinces	Types of support	Amount (10 mil RMB)	Targeted deadline	Targeted increase (mil heads)
04/19/2019	Guangdong	1, 2, 3	–	12/2020	3.6
09/07/2019	Hebei	3	66.8	–	–
09/30/2019	Fujian	2	–	12/2020	3.2
10/17/2019	Zhejiang	1, 2, 3	>54	12/2021	5.4
10/17/2019	Hubei	3	42	12/2022	11.7
10/24/2019	Henan	3	<6	12/2022	
11/18/2019	Chongqing	2, 3	66.5	–	–
11/23/2019	Jiangsu	3	39.6	–	–
11/25/2019	Liaoning	2	4.1	07/2019	–
11/25/2019	Anhui	3	13	–	–
11/26/2019	Tianjin	3	5.2	–	–
12/04/2019	Jilin	2	1.8	12/2020	–
03/11/2020	Hunan	1	27.8	–	–
03/19/2020	All	2	>44.4	12/2021	>150
03/26/2020	Heilongjiang	1, 2, 3	>3	12/2020	4.0
04/24/2020	Shandong	1	7.9	–	–
05/06/2020	Sichuan	3	15	12/2020	11.5

Notes: "-" means not available. *Types of support* is a categorical variable with 1 meaning access to credits, 2: discounts on loan interests, and 3: direct payments. Only a few policies set specific targets for production recovery by the deadlines. Most policies only claim to aim at “helping the recovery”. 6.5 RMB equals 1.0 USD.
Source: Links to the news are reported in Appendix A.

from January 2018 to September 2020. In contrast to the rising price of pork, prices of other meats stayed fairly stable over the whole period, except that prices of beef and mutton went up by about 10% during 2019.

2.2. Current policy responses

With pork being the dominant meat in the Chinese diet (Ortega et al., 2009b; 2015a), the pork price accounts for 9% of China’s Consumer Price Index (CPI). In the third quarter of 2019, the rising pork price started to push up CPI (Kang and Xiao, 2020) and created considerable pressure on the government to lower the price.

Since then, the central and provincial governments have launched financial supporting programs to help large-scale hog farms restore the production and increase hog outputs in 2020 and 2021. As shown in Table 1, all major hog-producing provinces have announced their recovery plans and corresponding financial support. The overall recovery target set by the central government was announced in March 2020, aiming to bring the annual hog production “close to” the pre-ASF level by the end of 2020 and back to the level by the end of 2021. Billions of RMB have been or will be put into the hog industry.

The recovery goals are ambitious, given that the annual hog production in 2019 was 150 million heads down from 2018 and the stock of sows by December 2019 was only 60% of its pre-ASF level. To increase the hog output by 150 million heads requires first increasing the stock of

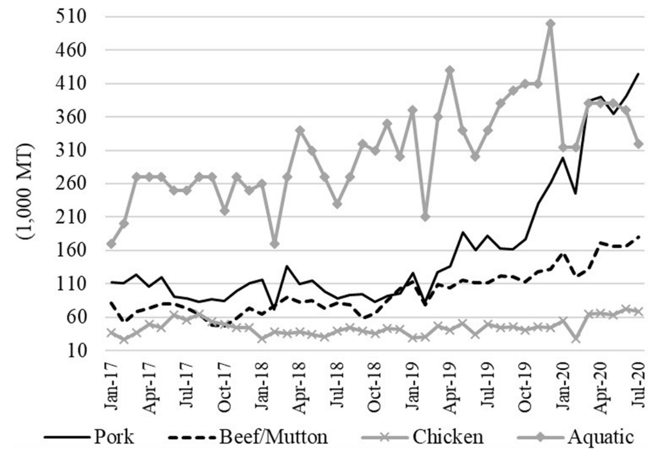

Fig. 3. China’s monthly import of meats. Source: http://www.customs.gov.cn/customs. Notes: Data cover January 2017 to July 2020.

sows by a large number. With one average sow producing 20–24 piglets a year in China, the increase in hog production implies an increase in the stock of sows by 6.3–7.5 million or 30–36% up from the 2019 year-end level. Knowing the biological lags, achieving such a large increase is quite difficult in a 2–3 year window. The fact that pork prices stayed at a high level by September 2020 is evidence of the biological lags (see Fig. 2). We revisit the biological cycle of hog production in Section 4.2.

China has also increased the import of meats since the outbreak of ASF. Fig. 3 shows a considerable increase in pork imports as well as imports of beef, mutton, and aquatic meats. By the end of 2019, the monthly pork import more than doubled the average level in 2017 and 2018. The total quantity of pork imported in 2019 is 68% higher than that of 2018. Even with such a sharp increase, the imported pork accounts for less than 5% of domestic pork production and consumption in 2019.

Another action taken by the government is the release of pork stockpiles to the market. From September to December in 2019, the central and several provincial governments released about 200,000 tons of frozen pork.[4] This amount, however, is trivial compared to the decrease in domestic pork production in 2019 – 11.5 million tons. The impact of providing frozen pork on pork prices is likely to be limited, also because frozen pork and fresh pork have a low degree of substitutability for pork consumers in China (Wang et al., 2018).

2.3. A potential complimentary policy

Given the government’s goal of lowering the pork price within a short period, what could be an alternative policy for ongoing policies? Demand theory suggests that increasing the supply of pork substitutes help lower the pork price. Prior studies show that chicken and beef are substitute meats for pork in China (Gould and Villarreal, 2006; Liu et al., 2009; Chen et al., 2016). The existing cross-price elasticities, though, are estimated using relatively dated price and consumption data (i.e., only up to 2011).

The production of cattle has an even longer biological cycle than hogs (i.e., about 300 days from gestation to finishing) and is more land intensive (Peters et al., 2014). China has no comparative advantage in producing cattle in the international market and has been importing a large volume of beef in recent years to meet its domestic demand (Brown et al., 2002; Waldron et al., 2010). Therefore, increasing the supply of beef is unlikely to be an effective alternative policy for achieving target

[4] News article available in Chinese: https://news.163.com/20/0106/21/F286GEBG000187R2.html.

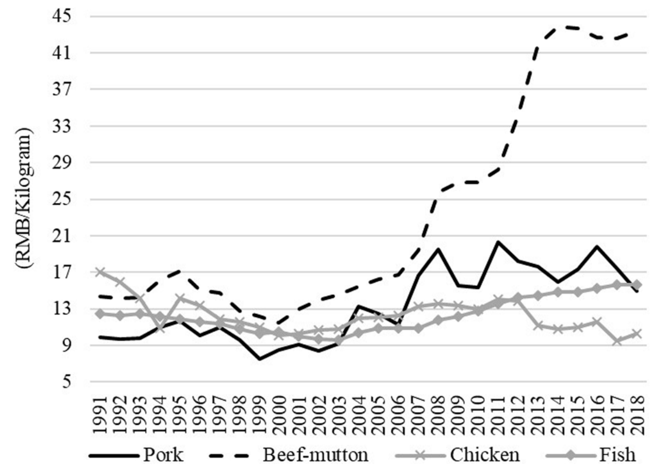

Fig. 4. Yearly real retail prices of meats in China. Source: Listed in Appendix A. Notes: Real prices are reported with 2000 as the base year. The price reported for beef-mutton is the average of the beef price and the mutton price weighted by their consumption shares.

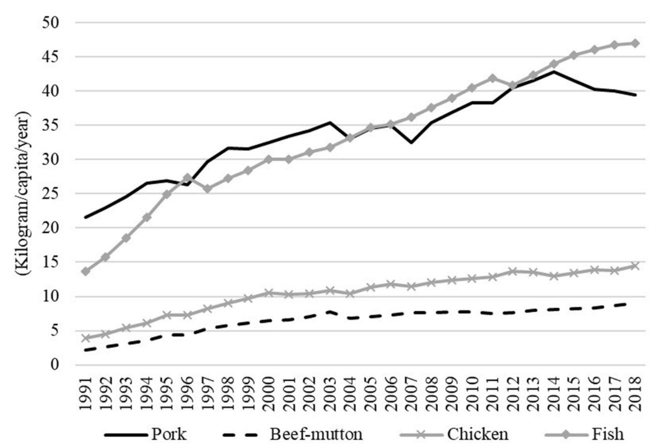

Fig. 5. Yearly per capita consumption of meats in China. Source: Listed in Appendix A.

reductions in the pork price.

Chicken, in contrast, involves a much shorter production cycle. As detailed in Section 4.2, the production of chicken is ASF-resistant and only takes about 70 days from hatching to finishing. Additionally, producing chicken is less environment, land, and labor intensive (Xin et al., 2020). We argue that the goal of suppressing pork prices could be achieved with less time, with perhaps less expenditure, by expanding the production of chicken. The fact that chicken only accounts for 12–13% of meat consumption in China also implies considerable room to increase chicken consumption.

3. Demand estimation

In order to compute price effects of alternative policies, we need updated estimation of price-quality relationships for major meats consumed in China. To do so, we update data on meat consumption and prices in China and estimate the demand of meats. Relying on the Inverse AIDS model, we identify a structural break in meat demand using the Maximum Likelihood criterion. Estimation outcomes suggest that chicken has been the major substitute for pork in recent years.

3.1. Data

We collect yearly meat consumption and price data from 1991 to 2018 to estimate meat demand in China. Four major meats, pork, poultry, beef and mutton, and fish are considered. Because chicken is the dominant poultry meat in China (Xin et al., 2020) and duck prices are not available, we use the price of chicken for poultry and "chicken" to refer to poultry. The consumptions of beef and mutton are combined and referred to as "beef-mutton", because each has a small share relative to other meats. The term "fish" refers to seafood and freshwater fish.

Fig. 4 summarizes real retail prices of the meats. Pork price increases by about 70% from 1991 to 2018, with most of the increase happening after 2006. The price of beef-mutton has gone up by 250% over the same period. Similarly, the increase becomes substantial after 2006. Chicken price falls slightly from about 14 RMB per kilogram to 10 RMB per kilogram. This is probably driven by the transformation from backyard to industrialized production of chicken (Xin et al., 2016). Fish price falls slightly in the 1990s before picking up by 2–3 RMB per kilogram by 2018 compared to the 1991 level.

We plot the per capita annual meat consumption in Fig. 5. As in many previous studies (Okrent and Alston, 2011), we use the total meat disappearance as the proxy for domestic meat consumption. Meat disappearance equals meat production minus net export. From 1991 to 2018, per capita meat consumption increases from 41.4 to 109.9 kg, an increase of more than 150%. More specifically, per capita consumption of pork increases from 21.6 to about 40 kg. Fish becomes the most consumed animal protein, not counting dairy or eggs from 2007 onwards, with a 240% growth from the 1991 level. Increases in the consumption of the other three meats are also considerable, although they still account for relatively small shares of the total consumption. The share of beef-mutton has been between 5 and 8%, and the share of chicken between 9 and 13%.

3.2. Estimation strategy

The AIDS model has been widely used for estimating demand systems of food and non-food products for its solid theoretical basis and simplicity over other demand models (Deaton and Muellbauer, 1980). In particular, it has been employed to estimate meat demand in many economies (Eales and Unnevehr, 1988; Moschini and Meilke, 1989), including China (Ortega et al., 2009a). The standard AIDS model describes consumption responses to exogenous prices, relying on the assumption of predetermined market prices. This assumption may not be appropriate in the context of perishable commodities whose production is subjective to biological lags and may not respond to price shocks within a quarter or a year. It is thus more appropriate to assume that the quantities supplied to the market are predetermined, or perfectly inelastic, and consumers' marginal utility from consuming these goods is reflected by prices to clear the market.

The Inverse AIDS (IAIDS) model was developed to better characterize the demand of meats which are perishable and generally consumed fresh (Eales and Unnevehr, 1994; Eales et al., 1997). It is developed from the distance function approach of duality consumption theory (Cornes, 1992). Similar to the AIDS model, adding-up, homogeneity, and symmetry constraints can be imposed on a system of equations when estimating the IAIDS model. Although other inverse demand systems, such as Inverse Rotterdam and Inverse Translog, and mix versions of these systems have been discussed in literature (Holt, 2002; Lee, 2007), our relatively small dataset does not allow us to estimate any mixed demand models and conduct formal tests to select the best model. Our priori choice of IAIDS is based on its well-established theoretical and empirical advantages and empirical popularity among alternative demand systems (Lee, 2007; Holt and Balagtas, 2009).

Given the four major meats in our context and the IAIDS framework, we build a system of three equations after dropping one equation under the adding-up constraint. Let w_i be the budget share of meat i, c_i a meat-specific constant term, q_j the per capita consumption of meat $j \in \{1,2,3,4\}$, t and t^2 the linear and quadratic time trends with meat-specific effects $a_i^{'}$ and $b_i^{'}$, and $\ln(Q) = \sum_{j=1}^{4} w_j \ln(q_j)$ the Stone quantity index which indicates the expenditure scale. Each equation in the system is expressed as:

$$w_i = c_i + \sum_{j=1}^{4} \gamma_{ji} \ln(q_j) + \beta_i \ln(Q) + a_i^{'} t + b_i^{'} t^2, i \in \{1,2,3\} \tag{1}$$

Taking the first-difference of variables to take care of the dynamic behavior of time-series data (Holt and Balagtas, 2009), we rewrite the equation system as:

$$dw_i = a_i + b_i t + \sum_{j=1}^{4} \gamma_{ji} \mathrm{d}\ln(q_j) + \beta_i \mathrm{d}\ln(Q), i \in \{1,2,3\}, \tag{2}$$

where $\mathrm{d}\ln(q_j)$ is the first-differenced log quantity and $\mathrm{d}\ln(Q)$ is approximated by $\sum_{j=1}^{4} w_j \mathrm{d}\ln(q_j)$.

We then compute the Marshallian own-quantity, cross-quantity, and scale flexibilities in a similar way as the own-price, cross-price, and expenditure elasticities computed in the AIDS model. The flexibility measures the percentage change in the marginal value of the commodity (i.e., its market price) caused by a 1% increase in consumption of a commodity. Formulas for quantity and scale flexibilities are, respectively (Eales and Unnevehr, 1993):[5]

$$f_{ij} = -\Delta_{ij} + \frac{\gamma_{ji} + \beta_i w_j}{w_i}, \tag{3}$$

where $\Delta_{ij} = 1$ for $i = j$ and zero otherwise, and

$$f_{is} = -1 + \frac{\beta_i}{w_i}. \tag{4}$$

Interpretations of flexibilities are similar to those of elasticities. A key difference, though, is that two commodities are termed "gross price substitutes" if their cross-price elasticity is positive, but are termed "gross quantity substitutes" if their cross-quantity flexibility is negative (Cornes, 1992). The scale flexibility is negative if the commodity is a normal good, while the corresponding income elasticity would be positive. For example, a scale flexibility of −1 implies that when expanding consumption of all commodities by 1%, the marginal value of a commodity would drop by 1% to maintain the utility of a consumer at the same level.

3.3. Structural changes in demand

During the period of interest, China has experienced substantial economic growth, leading to considerable increases in urbanization and real income. The consumption and preferences of food have experienced significant changes, too (Dong and Fuller, 2010). Preferences may be affected by various factors documented in studies on the long-term meat demand (Eales and Unnevehr, 1993; Hovhannisyan and Gould, 2014). For example, as health and environmental concerns prevail, consumers tend to substitute red meat for white meat or even vegetarian-meat products (Haley, 2001; Janssen et al., 2016). The rise of supermarkets changes food retailing and also affects consumers' attitudes to various food attributes (Ortega et al., 2015b).

To identify potential structural changes in meat demand, we follow the model set by Moschini and Meilke (1989) and specify a linear and monotonic time path h_t which captures a potential break in coefficients in Eq. (2) over time. Rewrite the equation as:

$$dw_i = (a_i + \delta_{0i} h_t) + b_i t + \sum_{j=1}^{4} (\gamma_{ji} + \delta_{ji} h_t) \mathrm{d}\ln(q_j) + (\beta_i + \delta_i h_t) \mathrm{d}\ln(Q), \tag{5}$$

Setting 1991 to be $t = 1$ and 2018 to be $t = 28$, for one structural change starting at $t = \tau_1$ and ending at $t = \tau_2$, the path in Eq. (3) is specified as:

$$h_t = 0, \ t = 1, \cdots, \tau_1 \tag{6a}$$

$$h_t = \frac{t - \tau_1}{\tau_2 - \tau_1}, \ t = \tau_1 + 1, \cdots, \tau_2 \tag{6b}$$

$$h_t = 1, \ t = \tau_2 + 1, \cdots, 28. \tag{6c}$$

The specification allows us to estimate the model using the Maximum Likelihood Estimation (MLE) method for all possible τ_1 and τ_2 during the period of interest and search for the τ_1 and τ_2 that generate the largest likelihood statistic.

Summary statistics of the data used for the estimation and regression outcomes are provided in Appendix B. We add a set of control variables to capture economic and demographic features of Chinese consumers, including per capita income, urbanization ratio, male population ratio, and senior population ratio. Variance in meat demand not explained by the economic and demographic variables is explained by the structural change.

MLE outcomes suggest that the optimal parameter estimates are $\tau_1 = 8$ and $\tau_2 = 26$ with a likelihood of 282.5. The estimated τ_1 and τ_2 imply a structural change starting in 1999 and ending in 2016.[6] The timing of this change aligns with the general economic development path of China. Significant economic growth started in the late 1990s. China joined the World Trade Organization in 2001, which has since brought profound impacts to many aspects of the Chinese economy (Huang and Rozelle, 2003; Carter et al., 2009). Economic prosperity, growing openness to international markets, and domestic policy reforms have changed the food marketing environment for Chinese consumers and may have contributed to substantial shifts in consumer food demand similar to what has been observed in other Asian economies (Pingali, 2007). Urbanization also accelerated after 2000, which has caused profound changes in food supply systems and food cultures (Dong and Fuller, 2010; Ortega et al., 2015a; Ortega et al., 2015b). All these changes have influence on Chinese consumers' demand for food, including meats.

To confirm the significance of the structural change, we report likelihood ratio tests for the hypothesis of constant h_t-related coefficients over the period (see Appendix C). The hypothesis of no structural change is rejected at the 1% significance level, meaning that time-invariant coefficients are unable to characterize the demand from 1991 to 2018. A structural change needs to be considered. To examine the nature of this structural change, we group h_t-related coefficients into three subsets. Table A.5 suggests that coefficients of $\ln(Q)$ are not subject to a structural change. The hypothesis of constant intercepts and quantity coefficients is rejected, implying significant changes in own- and cross-quantity flexibilities.

[5] This linear approximate flexibility formula (3) has been widely used since Chalfant (1987) and is shown to be a good approximation of the actual value (Green and Alston, 1990). Using the formula in Eales and Unnevehr (1994) generates highly consistent flexibilities.

[6] Holt and Balagtas (2009) propose an econometric model to estimate structural changes that are smooth over time and potentially non-monotonic. The structural change can be characterized by a nonlinear function, for instance, an exponential or a logistic function. This model, however, requires many more observations to estimate, which our sample does not provide. We also estimate equation (2) by interacting h_t with $\ln(q_j)$ and $\ln(Q)$ first and then taking the first-difference. Outcomes are consistent with the outcomes presented here. Yet that specification is unable to take care of the segmentation in our data (i.e., the 2003 dummy variable) and does not have as high a goodness of fit for the pork equation, which is the key equation in our context. Our preferred specification is equation (5).

Table 2
Estimated flexibilities based on the IAIDS model.

	Pork	Beef & Mutton	Chicken	Fish	Scale
1991–98 (pre-change)					
Pork	−0.84	−0.88	−1.51	−1.98	−1.42
	(0.54)	(0.21)	(0.22)	(0.45)	(1.04)
B&M	−0.06	−1.08	−0.08	−0.24	−1.05
	(1.53)	(1.00)	(0.77)	(0.99)	(2.34)
Chicken	−0.02	0.16	−0.76	0.24	−0.94
	(0.49)	(0.50)	(0.54)	(0.53)	(0.94)
Fish	0.01	0.14	0.24	−0.57	1.33
	(0.58)	(0.14)	(0.16)	(0.44)	(1.08)
2018 (post-change)					
Pork	−3.44	−0.33	−0.38	0.08	−4.06
	(1.15)	(0.34)	(0.22)	(1.54)	(1.24)
B&M	1.34	2.05	−1.22	−0.45	1.72
	(0.69)	(1.13)	(0.60)	(1.25)	(2.49)
Chicken	−0.60	−3.74	2.32	0.84	−1.18
	(0.80)	(1.43)	(1.54)	(1.63)	(1.61)
Fish	1.38	−0.57	0.27	−1.00	0.08
	(0.93)	(0.50)	(0.30)	(1.48)	(1.42)

Notes: Bootstrapped standard errors are in the parentheses. For the pre-change period, the mean is the average of flexibility values respectively computed for each of the eight years. Outliers generated in bootstrapping are excluded from the calculation of standard errors. Bootstrapping procedure follows Freedman and Peters (1984) with extreme simulated coefficients dropped.

3.4. Estimation outcomes

Using the first-differenced data for estimation, we effectively have $27 \times 3 = 81$ observations for estimating the system of three equations for four meats. Potential covariance in the error terms across the three equations in the system is taken care of by using the seeming-related regression (SUR) model. Augmented Dick-Fuller tests suggest no evidence of unit root in the first-differenced expenditure share or quantity variables. We construct joint F-tests on the lagged residuals across equations and find no evidence of autocorrelation in residuals (see Appendix C). Regression outcomes are reported in Table A.4.

Before the structural change, flexibilities are computed based on Eqs. (3) and (4), and after the structural change, flexibilities are derived from Eq. (5) as:

$$f_{ij} = -\Delta_{ij} + \frac{(\gamma_{ji} + \delta_{ij}) + (\beta_i + \delta_i)w_j}{w_i}, \tag{7}$$

where $\Delta_{ij} = 1$ for $i = j$ and zero otherwise, and

$$f_{is} = -1 + \frac{\beta_i + \delta_i}{w_i}. \tag{8}$$

In the upper panel of Table 2, we report pre-change estimated flexibilities based on mean values of w_i. In the lower panel, we report the post-change estimates in 2018, which is the base year for our simulations. In both pre- and post-change periods, pork has a negative and statistically significant own-quantity flexibility, implying that it is an ordinary good. Its estimated own-quantity flexibility is −3.4 in 2018, suggesting that the demand is highly inelastic and echoing prior studies (Chen et al., 2016). This flexibility means that increasing pork supply by 1% results in a 3.4% drop in pork price. The scale flexibility is negative, indicating that pork is a normal good.

Chicken is neither an inferior good, given its negative yet insignificant scale flexibility, nor a Giffen good given its insignificant own-quantity flexibility. An increased chicken supply would not cause its price to increase significantly. Chicken serves as a substitute for pork in both periods given the negative pork-chicken flexibility, echoing prior studies (e.g., Chen et al., 2016). To be specific, the cross-quantity flexibility is −0.4 in 2018 and statistically significant at 10% level. It implies that a 1% increase in chicken supply lowers the pork price by 0.4%. Admittedly, this cross flexibility is not as precisely estimated as the own flexibility of pork. In Section 4.2, we show the robustness of our policy simulations by considering alternative values of this cross flexibility. Beef-mutton and fish are not significant substitutes for pork in 2018, though they are in the pre-change period. Chicken is also a substitute for beef-mutton and *vice versa*.

4. Policy analysis

Estimated meat demand suggests that chicken is a major substitute for pork. We also need information on production cycles of pork and chicken to quantify price impacts of alternative policies within a period of time. This section starts with a comparison of production cycles and costs of the two meats. Policy outcomes are then simulated based on estimated flexibilities, production cycles, and production costs of pork and chicken. A set of sensitivity tests are conducted. Implications of alternative policies on consumer welfare, producers, and the government are discussed, as well as the limitations of the simulation analysis.

4.1. Production cycles of pork and chicken

The production cycle of hogs is much longer than that of chickens. As summarized in Table 3, large-scale hog farms in China need to first build large-scale pig sheds, which takes 6–10 months to construct. From gestation to finishing, there is another window of about 300 days. In contrast, from eggs to chickens, the cycle takes only about 75 days. Additionally, building chicken production plants takes much less time due to their relatively simple structure and attached facilities.

Table 3 suggests that the total cost of hog production for large-scale farms is about 1700 RMB per head in 2017. The total cost of chicken

Table 3
Production cycles and costs of hog and chicken in China.

	Hog		Chicken		
Item	Time (days)	Cost (RMB/head)	Time (days)	Cost (RMB/head)	Hog-equivalent cost (RMB/head)
Construction	180–300	150	72–120	0.4	42
Gestation	114	648	–	–	–
Farrowing/Hatching	21	75	22	2–3	105–158
Nursery	42–56	202	28–35	1.3	68
Growing/Finishing	115–120	388	21–28	8.4	441
Labor		165/109		1.0	52.5
Other costs		90		2.4	126
Total, excl. house	292–311	1568/1512	71–85	15.1–16.1	793–845

Notes: "-" means not available. Housing cost is computed assuming a large basic pig shed can be used for 15 years and host 5,000 pigs a time, and chicken shed for 100,000 heads a time. *Other costs* include feed, veterinary drugs and vaccination, water, electricity, and loss due to natural mortality of animals. The chicken cost is converted to hog-equivalent cost in the last column based on the fact that one hog yields meat equivalent to that of 52.5 chickens.
Source: https://www.htfc.com/wz_upload/png_upload/20180413/1523602567467fb62bf.pdf, CARS (2019), and http://www.czeps.cn/yangjijishu/79495.html.

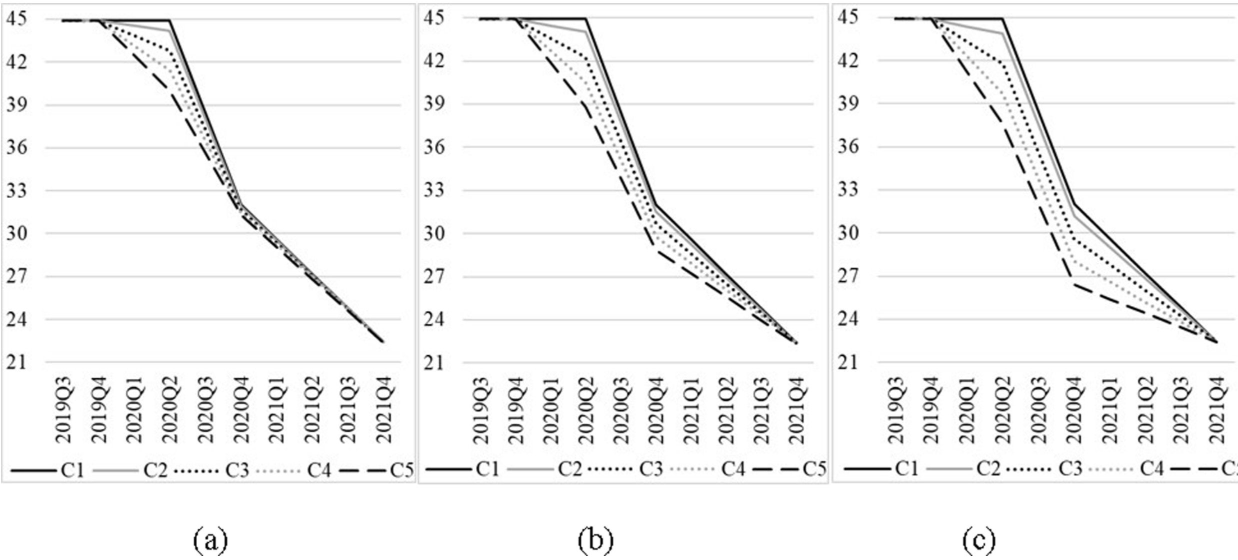

Fig. 6. Dynamics of the pork price under alternative policies. Source: Authors' simulation outcomes. Notes: Real prices are reported in the unit of RMB per kilogram with the RMB in 2000 as the baseline (vertical axis). The five cases are denoted by C1-C5 and refer to alternative budget splits. C1: all subsidies are spent on hog farms. C2-C5: 90%, 70%, 50% and 30% of 2020 subsidies are spent on hog farm and the rest on chicken farms, respectively. The horizontal axis indicates the year and the quarter. For example, 2021Q4 means the fourth quarter of 2021. In all three panels, $f_{pp} = -3.4$. Panel (a): $f_{pc} = -0.4 \times 80\%$. Panel (b): $f_{pc} = -0.4$. Panel (c):$f_{pc} = -0.4 \times 120\%$.

production is about 15–16 RMB per head. After slaughtering, each hog produces 77.5–78.2 kg of pork, while a slaughtered chicken weighs 1.3–1.5 kg. Every 52–53 chickens provide the same amount of meat that one hog does. Altogether, the effective production cost of meat from hog is about twice as much as that from chicken.

4.2. Simulation-Based policy analysis

As shown in Fig. 2, the national average price of pork in the second half of 2019 reached 44.9 RMB per kilogram. We consider a goal of suppressing the price to its pre-ASF level by the end of 2021 (i.e., about 22.4 RMB per kilogram), with the price down to $\frac{22.4}{70\%} = 32.0$ RMB per kilogram or lower by the end of 2020. These two levels are set based on the policy goals announced by the central government in March 2020 (see Table 1) that the pork market will be brought "largely back to normal by the end of 2020" and "normal by the end of 2021". Interpreting the two targets by price, we argue, reflects the essence of the targets, because the actual pressure on the government comes from rising pork prices and CPI.

To achieve the goals and with the estimated own-quantity flexibility of pork (see Table 2), we find that the annual production of pork would need to increase by 8.5% in 2020 from 2019 and by 8.8% in 2021. Because the government aims to promote large-scale hog farms, we assume that all additional hogs will come from newly built large farms that produce 10,000 hogs per year. According to Table 1, governments subsidize hog farms at 100–300 RMB per hog produced. Other parameters used in the simulation are found in Table A.6.

In this partial equilibrium simulation model, our key assumptions are that all flexibilities and quantities consumed for beef-mutton and fish are fixed at their 2018 values and other ways of increasing meat supply, such as meat imports and releasing meat stockpiles, play no role. Actions taken by the private sector are abstracted away, though new farms are constructed and managed by farmers, not the government. These assumptions help us focus solely on the effects of alternative subsidy policies on pork consumption and price.

The simulation covers from the third quarter of 2019 through the end of 2021. With a detailed procedure described in Appendix D, the major simulation steps are summarized below.

Table 4
Government budget and pork consumer surplus under alternative policies.

		Two-year budget (billion RMB)	Budget saved (billion RMB)	Budget saved (%)	CS increase (%)
Case 2	(a)	17.4	0.1	0.6	1.50
	(b)	17.2	0.3	1.7	0.92
	(c)	16.9	0.6	3.4	0.44
Case 3	(a)	17.1	0.4	2.3	3.25
	(b)	16.4	1.1	6.3	1.92
	(c)	15.6	1.9	10.9	0.74
Case 4	(a)	16.8	0.7	4.0	3.45
	(b)	15.6	1.9	10.9	1.92
	(c)	14.2	3.3	18.9	0.35
Case 5	(a)	16.5	1.0	5.7	2.27
	(b)	14.7	2.8	16.0	1.05
	(c)	12.6	4.9	28.0	−0.69

Notes: All values of changes are computed relative to case 1 under a particular setup. (a), (b), and (c) refer to panels (a), (b), and (c) in Fig. 6.
Source: Authors' simulations.

(1) Plug in the estimated impacts of increasing meat supply on meat prices, namely the estimated flexibilities and other parameters like target price reductions.
(2) Given the 2020 and 2021 year-end target price reductions, compute corresponding increases in pork and chicken supply based on the flexibilities.
(3) Given the production scale of farms, convert the increase in meat supply to the increase in the number of farms.
(4) Compute corresponding subsidies needed for building the farms.
(5) Track price dynamics and compare government expenditure under alternative budget splits between hog and chicken farms during the period.

To compare various policy designs, we choose five different budget allocations over the 30-month period. For simplicity, the 2021 budget may only be allocated on hog farms to ensure a sufficient increase in pork supply in the long-run, while the split of the budget in 2019 and 2020 remains flexible. We then simulate pork prices for each quarter under alternative budgets and show the outcomes in Fig. 6. From case 1 to case 5, an increasing share of the subsidy budget is allocated to chicken farms. We show the robustness of the simulation outcomes by varying the value of cross-quantity flexibility of pork on chicken, f_{pc}. Specifically, f_{pc} equals -0.4 in panel (b) of the figure as the base value, while f_{pc} equals the base value multiplied by 80% and 120% in panel (a) and (c), respectively.

Subsidizing pork farms increases pork supply after four quarters, while subsidizing chicken farms increases chicken supply after two quarters only, thanks to the shorter production cycle of chicken. Given the substitutability of pork and chicken, consumers voluntarily consume more chicken and less pork with an increased chicken supply, causing the pork price to drop.

In case 1 of panel (b), all subsidies go to hog farms (i.e., 17.5 billion RMB). No price reduction happens until the fourth quarter of 2020. In case 2, if the government first spends 10% of the budget on chicken farms, the price starts dropping in the first quarter of 2020. Additionally, the total expenditure would be 1.7% lower than in case 1. If 50% of the subsidies is allocated to chicken farms (i.e., case 4), it would save as much as 10.9% of the total expenditure, or 1.9 billion RMB (see Table 4).

Table 4 also shows that government costs saved in cases 2 to 4 of panel (a) are relatively small compared with panel (b), while those of panel (c) are relatively large, because price reductions driven by subsidizing chicken farms essentially depend on the *relative efficiency* of increasing chicken supply in pressing down the pork price. A larger f_{pc} relative to f_{pp} (own-quantity flexibility of pork) implies a larger percentage decrease in the pork price for one percentage increase in chicken supply. Across the three panels, our main conclusions are consistent in the relative magnitude of f_{pc} and f_{pp}: allocating some subsidies on chicken farms 1) helps suppress the pork price 6 months earlier, and 2) saves on the total expenditure of the government for the same price reduction by the end of 2021.

To measure the welfare effect of alternative policies, we compute the consumer surplus (CS) of pork. The idea is to express the price of pork as a function of meat quantities based upon Eq. (1). The price of meat i can be written as:

$$p_i = \frac{E}{q_i}\left(c_i + \sum_{j=1}^{4}\gamma_{ji}\ln(q_j) + \beta_i \ln(Q) + a_i t + b_i t^2\right), \tag{9}$$

where $E = \sum_{i=1}^{4} p_i q_i$. With p_i^* and q_i^* representing equilibrium price and quantity of meats, the CS of a meat is found by taking the integral with estimated parameters from the IAIDS model (see Appendix D for detailed derivation):

$$CS_i = \int_0^{q_i^*} p_i(q_i)dq_i - p_i^* q_i^*. \tag{10}$$

With parameters set at values of panel (b), the CS in case 2 increases from case 1 by 0.9%, the CS in case 3 increases by 1.9% and so on. The CS reaches its largest value, when 30-50% of the budget in 2020 is allocated to chicken farms. Given the population of China, even a 1–2% increase in the CS would be substantial. Indeed, this is only a lower bound of the CS increase from subsidizing chicken farms, because we use yearly average prices and quantities to estimate the CS and do not consider the value of suppressing the price of pork half a year earlier when subsidizing chicken production.

Our sensitivity analysis using flexibility values under panels (a) and (c) shows consistent results with the baseline. Notice that panel (a) generates higher CS values than the baseline in all cases, though its pork price reductions in 2020 are relatively small. It might seem counterintuitive, except that, with the same pork price reduction by the end of 2021, a larger increase in pork consumption is achieved in panel (a) than in the baseline. As a result, the total increase in pork CS is relatively high. The opposite is true for panel (c). In case 5 of panel (c) where the pork price is largely brought down by an increase in chicken consumption, pork CS is even smaller than in case 1 due to a much smaller pork consumption in 2020 and 2021. These simulation outcomes highlight the tradeoff between suppressing the pork price by increasing the supply of a substitute and recovering pork supply over the long-run as the government tries to protect the welfare of consumers.

4.3. Further discussion

Subsiding chicken production has multiple impacts on the meat market and consumers. In addition to increasing the CS, the structure of meat consumption in China can be improved by increasing the consumption of chicken, a white meat, from the perspective of health. The share of chicken out of total meat consumption in 2019 was only 13%. Under the baseline simulation, this percentage could be pushed up to 15.7% in case 2 and 22.3% in case 5 in 2021.[7] As consumers substitute expensive pork for relatively cheap chicken in the short-run, their diet preferences, reinforced by food processing and food service industries' adaptation, may change towards white meat in the long-run and become more in line with diets in advanced economies.

Replacing hog farms with chicken farms also has environmental and resource benefits, because chicken production causes less pollution and has a much higher feed conversion rate (Xin et al. 2020). Looking back, the environmental damage of hog farms was exactly the reason why many local governments prohibited the construction of new hog farms and removed a number of existing hog farms in 2017 (Gu and Josephine, 2017), which might have aggravated the fall in pork supply in 2019.

Given alternative methods of increasing pork supply, one might argue that China could lower pork prices by importing more pork. Doing so is likely to have limited impacts on pork prices for several reasons. First, given China's substantial domestic pork consumption and the ASF-caused production loss of over 21%, the world market lacks this scale of extra pork supply. As mentioned in Section 2.2, even doubling or tripling the pre-ASF imports of pork would only marginally make up the lost domestic supply. Second, trade policies and biosafety measurements may add uncertainty and impede imports of pork. For example, ASF has been spreading outside China. Importing runs a risk of spreading the virus to the domestic hog industry. Another concern is the ongoing trade war between the U.S. and China with the U.S. being a major pork exporter to China. Chinese pork imports from the U.S. are sometimes levied a high tariff and other times none.

Furthermore, import of pork tends to be impeded by the spread of COVID-19. For example, the cargo ships have extended docking times at ports due to reduced workforce and additional inspection and quarantine procedures at many logistic sites (AJOT, 2020; WPSP, 2020) and additional inspection and quarantine procedures. Processing plants in exporting countries like the U.S., Brazil, and Germany also face reduced capacity due to an infected workforce (Lakhani 2020; The Pig Site, 2020; Noryskiewics, 2020). Imports of COVID-positive foods are banned by China (Reuters, 2020). Finally, the overseas shipment of pork is mostly frozen and ends up in food processing and/or food service sectors. In retail markets in China, frozen pork and fresh pork have a low degree of substitutability (Wang et al., 2018).

4.4. Caveats and future research

A few caveats of our analysis are worth discussing. First, the long-run dynamics of pork prices, the hog cycle, are not explicitly incorporated in the simulation model. One hog cycle in China is 3–4 years (Chavas and

[7] Substituting pork with chicken on a large scale faces challenges. In particular, cuisine culture may play a key role. Traditionally, chicken is considered as a side meat for Chinese consumers, and pork as a red meat has taste and texture attributes not available in chicken. It can be difficult to replace pork with chicken on a large scale. The taste difference between pork and chicken is likely to narrow as pork becomes leaner (i.e., with less saturated fat).

Pan, 2020). A critical downside of building a large number of new hog farms within 2 years is increasing the risk of pushing the price so low in later years that hog farmers would experience losses after 2021. Historical data suggest that experiencing losses during low-price periods of the hog cycle is not uncommon for Chinese hog farmers (CARS, 2019). If a large number of hog farms were built under subsidies, and many existing farms increased production without subsidy, a market overshooting is likely to occur. The alternative policy that we propose may henceforth benefit hog producers in the long-run by helping mitigate market overshooting.

Second, we have not studied the impact of alternative policies on the structure of pork and chicken industries. For example, heavy subsidies on large-scale hog farms tend to increase the concentration of hog production in China in the long-term, especially given that many small-scale hog producers were driven out of production by ASF. The transformation from backyard production to modern hog farms in China is likely to be accelerated by subsidies, leading to a long-run increase in industry productivity (Qiao et al., 2016).

Third, the estimated flexibilities are assumed to be constant in simulations. Strictly speaking, these flexibilities may vary with the changes in meat supply. In particular, the substitutability of chicken for pork (i.e., f_{pc}) could decrease as more chicken is consumed relative to pork. Though we do not explicitly allow the flexibilities to vary over the 30-month window, we do show in Fig. 6 that our simulation outcomes are fairly robust with different values of f_{pc}. Even if f_{pc} falls slightly as chicken supply increases, our major conclusions hold. We leave more accurate characterizations of the dynamics in flexibilities for future research.

5. Concluding remarks

In this paper, we discussed policy responses to the sharp decline in hog inventory due to the 2018 ASF outbreak in China – the world's largest producer and consumer of pork. The reduction in hog production and inventory resulted in substantial price jumps in 2019, which pushed the government to carry out a series of subsidizing programs to help hog farms, aimed at restoring hog inventory and boosting pork supply within a 2–3 year window.

To evaluate effectiveness and efficiency of the current policy, we employed 1991–2018 meat consumption and price data to estimate China's meat demand and identified a gradual structural change in demand during the same period. Based on the updated own- and cross-quantity flexibilities of pork, we estimated the price dynamics under alternative subsidy splits on hog and chicken farms and changes in the consumer surplus.

Simulations showed that allocating some of the subsidies to chicken farms would suppress the pork price 6 months earlier and reduce government expenditure. For example, allocating half of the pork-exclusive budget to chicken farms in 2019–2020 could save the government 10.9% of its expenditure over a 30-month window to achieve the same reductions of the pork price. Moreover, the surplus of pork consumers may be increased by about 2%. These findings are of relevance to other countries that suffer or might suffer from ASF.

Author contribution

Meilin Ma: Conceptualization, Methodology, Software, Formal Analysis, Writing-Original draft, Writing-reviewing and editing. **H. Holly Wang:** Conceptualization, Methodology, Formal Analysis, Writing-reviewing and editing. **Yizhou Hua:** Data Curation, Writing-reviewing and editing. **Fei Qin:** Data Curation, Writing-reviewing and editing. **Jing Yang:** Data Curation

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Appendix A. List of news about policy responses to the African Swine Fever in China

Table A.1 summarizes news of supporting programs on hog farms launched by the central and provincial governments.

Table A1
News of subsidy programs for major hog producing provinces.

Date of news	Provinces	Web links (all news in Chinese)
04/19/2019	Guangdong	https://news.163.com/19/0725/21/EKVB5HBN0001875N.html
09/07/2019	Hebei	http://www.gov.cn/xinwen/2019–09/07/content_5428110.htm
09/30/2019	Fujian	https://finance.sina.cn/2019–09-30/detail-iicezzrq9445237.d.html?from=wap
10/17/2019	Zhejiang	http://news.cctv.com/2019/10/03/ARTIbA7moPAbU4Hoeuuo6LR6191003.shtml
10/17/2019	Hubei	http://www.chinapig.cn/html/n2/1/2019/10/17/2019/10/1710423406.shtml
10/24/2019	Henan	http://www.ketaijituan.com/ktc_5/20191024171649348.htm
11/18/2019	Chongqing	http://www.gov.cn/xinwen/2019–11/18/content_5453063.htm
11/19/2019	Jiangxi	http://paper.people.com.cn/rmrb/html/2019–11/19/nw.D110000renmrb_20191119_7-02.htm
11/23/2019	Jiangsu	http://www.gov.cn/xinwen/2019–11/23/content_5454893.htm
11/25/2019	Liaoning	https://m.chinanews.com/wap/detail/zw/sh/2019/11–25/9016400.shtml
11/25/2019	Anhui	https://m.chinanews.com/wap/detail/zw/sh/2019/11–25/9016400.shtml
11/26/2019	Tianjin	http://www.chinapig.cn/html/n2/1/2019/11/26/2019/11/269475906.shtml
12/04/2019	Jilin	http://www.xinhuanet.com/2019–12/04/c_1125308647.htm
12/06/2019	Shanxi	http://www.sx.xinhuanet.com/2020–01/09/c_1125439567.htm
03/11/2020	Hunan	https://kuaibao.qq.com/s/20200311A0PCRE00?refer=spider
03/19/2020	All	https://news.ifeng.com/c/7uyQX5VC8FE
03/26/2020	Heilongjiang	http://www.caaa.cn/show/newsarticle.php?ID=404419
04/24/2020	Shandong	http://finance.eastmoney.com/a/202004241466402848.html
05/06/2020	Sichuan	http://finance.eastmoney.com/a/202005061474943927.html

Appendix B. Data sources

Sources of data used in the demand estimation are listed in Table A2.

Table A2
Data sources of variables used in the demand estimation.

Variables	Period	Data source	Publisher/Web site
Pork/Beef/Mutton prices	1991–2003	Food and Agriculture Organization	http://www.fao.org/faostat/en/#home
	2004–2016	China's Yearbook of Agricultural Price Survey	Beijing: China Statistics Press
	2017–2018	China's Ministry of Agriculture and Rural Affairs	http://www.xmsyj.moa.gov.cn/jcyj/
Chicken prices	1991–2003	Food and Agriculture Organization	http://www.fao.org/faostat/en/#home
	2004–2005	China's Yearbook of Agricultural Price Survey	Beijing: China Statistics Press
	2006–2018	China's Ministry of Agriculture and Rural Affairs	https://cif.mofcom.gov.cn/cif/html/
Fish price index	1991–2018	China's National Bureau of Statistics	http://data.stats.gov.cn/
Pork/Beef/Mutton/Poultry per capita consumption	1991–2003	Food and Agriculture Organization	http://www.fao.org/faostat/en/#home
Pork/Beef/Mutton/Poultry production	2004–2018	China's National Bureau of Statistics	http://data.stats.gov.cn/
Fish production	2004–2018	China's Fishery Statistical Yearbook	Beijing: China Agriculture Press
Pork/Beef/Mutton/Poultry imports/exports	2004–2018	China's Customs Statistical Yearbook	Beijing: China Customs Press
Fish imports	1993–2018	China's Fishery Statistical Yearbook	Beijing: China Agriculture Press
Fish exports	1991–2018	China's Fishery Statistical Yearbook	Beijing: China Agriculture Press

Notes: Data of fish imports in 1991 and 1992 are not available. We extrapolated the data based on the rate of change between 1993 and 1994 values. If 1994 value is A and 1993 is B, then we set 1992 value as $B \times B/A$ and 1991 value as 1992 value multiplied by B/A. Extrapolating trade data tends to have little impact on the apparent consumption, because net export accounts for less than 2% of consumption in the 1990s. Prices of fish are computed using the price index with 1983 FAO fish price as the baseline. Demographic variables and per capita income and GDP information are obtained from the National Bureau of Statistics of of China.

Appendix C. Summary Statistics and estimation outcomes

The table below summarizes all variables used in the estimation of meat demand in China from 1991 to 2018. Units of measurements are specified in the notes under the Table A.3.

Estimation outcomes from the first-differenced IAIDS model are reported in Table A4. As shown in equation (2), the dependent variables are dw_i or first-differenced meat expenditure shares. The system of three equations is estimated using the seemingly unrelated regression (SUR) model and a maximum likelihood estimator. The model characterizes meat demand in China fairly well, given that the R^2 and χ^2 values are comparable to prior studies (e.g., Dong and Fuller, 2010). Coefficients of first-differenced $\ln(q_i)$ are mostly significant, while those of the first-differenced $\ln(Q)$ are not. Several coefficients of the h_t-interactions are significant, implying significant structural changes in the meat demand.

To test autocorrelation in the error terms, we construct a two-stage joint F-test. In the first stage, we use the SUR model to estimate equation (5) for each meat and obtain the residuals. In the second stage, we run a VAR(1) model to test if the coefficients of all lagged residuals are jointly zero. Denoting residuals of the first-differenced pork, beef/mutton, and chicken SUR equations by subscript $\widehat{\epsilon}_{1t}$, $\widehat{\epsilon}_{2t}$, and $\widehat{\epsilon}_{3t}$, respectively, we construct the VAR(1) model as:

$$\begin{bmatrix} \widehat{\epsilon}_{1t} \\ \widehat{\epsilon}_{2t} \\ \widehat{\epsilon}_{3t} \end{bmatrix} = \begin{bmatrix} \theta_{11} & \theta_{12} & \theta_{13} \\ \theta_{21} & \theta_{22} & \theta_{23} \\ \theta_{31} & \theta_{32} & \theta_{33} \end{bmatrix} \begin{bmatrix} \widehat{\epsilon}_{1,t-1} \\ \widehat{\epsilon}_{2,t-1} \\ \widehat{\epsilon}_{3,t-1} \end{bmatrix} + \begin{bmatrix} e_{1t} \\ e_{2t} \\ e_{3t} \end{bmatrix}$$

We test for autocorrelation in residuals using the null hypothesis, $H_0 : \theta_{1i} = \theta_{2i} = \theta_{3i} = 0$ for $i \in \{1, 2, 3\}$. If not rejecting H_0, there is no evidence for autocorrelation in the residual of equation i with its own lagged term and other lagged residual terms. All the tests fail to reject H_0 with the probability greater than the F-statistics being 0.54, 0.22, and 0.83 for pork, beef/mutton, and chicken equations, respectively.

To further understand the structural change, we perform a set of tests on the coefficients of h_t-interactions following the work of Moschini and Meilke (1989). We estimate the system of equations with and without particular constraints and perform a likelihood ratio test on each pair of specifications. For example, we estimate the demand system with structural change variables, h_t and its interaction terms, and save its log-likelihood ratio, $\ell(\theta_1)$ where θ_1 represents the corresponding set of estimates. We then estimate the system with no structural change variable and save another log-likelihood ratio, $\ell(\theta_2)$. With the two log-likelihood ratios, we compute the likelihood-ratio test statistic:

$$\lambda = -2[\ell(\theta_1) - \ell(\theta_2)]$$

The null hypothesis is that the two sets of estimates are statistically indifferent. Comparing the test statistic against the χ^2 distribution, we can decide whether the null hypothesis should be rejected. In this example, if the null hypothesis is rejected, we conclude that structural changes in demand are significant and a single set of coefficients throughout the period are unable to correctly characterize the demand system. Test outcomes are reported in Table A.5 and discussed in Section 3.3.

Table A3
Summary statistics of dependent and explanatory variables.

Variables	Mean	Std. dev.	Min	Max
Pork price	15.27	7.54	5.09	28.67
Beef-mutton price	28.31	20.07	7.42	64.02
Chicken price	13.19	2.94	8.54	18.51
Fish price	13.71	5.11	6.42	23.52
Pork consumption per capita	33.82	5.94	21.58	42.79
Beef-mutton consumption per capita	6.52	1.90	2.19	8.99
Chicken consumption per capita	10.51	3.01	3.93	14.49
Fish consumption per capita	33.42	9.46	13.71	46.92
Other control variables				
Yearly per capita income	9.64	8.39	0.98	28.23
Yearly urbanization ratio (%)	42.43	10.66	26.94	59.58
Yearly senior population (%)	8.07	1.72	5.99	11.94
Yearly male population (%)	51.29	0.20	50.82	51.63

Notes: The number of observations is 28. Unit for prices is real RMB/kilogram and for per capita consumption is kilogram. Unit for income per capita is 1,000 real RMB. The real RMB is computed using 2000 as the base year.

Table A4
Estimation outcomes from the IAIDS model.

Equation	Pork	Beef/Mutton	Chicken
Intercept	0.15*	0.01	−0.10***
	(0.09)	(0.02)	(0.03)
Log pork consumption	0.58***	−0.03	−0.25***
	(0.15)	(0.07)	(0.06)
Log beef-mutton consumption	−0.03	0.02	0.12***
	(0.07)	(0.07)	(0.04)
Log chicken consumption	−0.25***	0.12***	0.15***
	(0.06)	(0.04)	(0.04)
Log fish consumption	−0.30***	−0.10***	−0.02
	(0.10)	(0.03)	(0.04)
Log Stone quantity index (scale)	−0.42	−0.09	0.19
	(0.47)	(0.13)	(0.16)
h_t	0.28	−0.11*	−0.24***
	(0.20)	(0.06)	(0.07)
Log pork consumption	−1.05*	0.13	0.21
interacted with h_t	(0.57)	(0.17)	(0.19)
Log beef-mutton consumption	0.13	0.50***	−0.41***
interacted with h_t	(0.17)	(0.16)	(0.10)
Log chicken consumption	0.21	−0.41***	0.12
interacted with h_t	(0.19)	(0.10)	(0.10)
Log fish consumption	0.71*	−0.21*	0.09
interacted with h_t	(0.40)	(0.13)	(0.14)
Log Stone quantity index (scale)	−0.55	0.65	−0.20
interacted with h_t	(1.61)	(0.43)	(0.54)
Control variables	Yes	Yes	Yes
Trend	Yes	Yes	Yes
R^2	0.58	0.76	0.67
χ^2	49.06	101.64	87.87

Notes: The number of observations is 27. * p-value < 0.1, ** p-value < 0.05, and *** p-value < 0.01. Standard errors are in the parentheses. All consumption variables are first-differenced. h_t is the structure parameter defined in Section 3.3. Control variables are listed in table A.3 and includes an indicator of years after 2003.

Table A5
Coefficient consistency in the IAIDS Model.

Hypothesis	#Restrictions	Likelihood-ratio test statistic	Prob $>\chi^2$
No structural change in			
All coefficients	18	15.06	0.002
Intercept coefficients	3	3.07	0.08
Scale coefficients	3	0.46	0.50
Quantity coefficients	12	3.20	0.07

Notes: The econometric specification is the same as that used for table 2, except that different sets of constraints are imposed to perform likelihood tests for different hypotheses.

Appendix D. Simulation parameters and procedure

The parameters used in our baseline simulations are summarized in Table A6.

For the following calculation, we take quarters 3 and 4 of 2019 as the reference point. The corresponding half-year consumption of pork is 19.0 million tons. To bring the price down to 32.0 RMB per kilogram by the end of 2020, the percentage decrease in price is:

$$\frac{44.9-32.0}{44.9}\times 100\% = 28.7\%.$$

Suppose that all subsidies are given to hog farms. Because the own-price flexibility of pork is -3.4, the supply of pork has to increase by $\frac{28.7\%}{3.4}=8.5\%$. Thus, the 2020 year-end price is achieved by increasing the output of hogs in 2020 by 8.5% over the *yearly* consumption of 2019:

$$\frac{19.0\ \ mil\ \ ton\times 2\times 8.5\%}{78\ \ kg} = 41.1\ \ mil\ \ heads.$$

If each large farm produces 10,000 hogs a year, $\frac{41.1mil}{10{,}000}\approx 4114$ new hog farms need to be built. For each farm, the government subsidizes 200 RMB per hog produced or 8% of the construction and yearly operational costs. The government's 2020 all-hog budget hence is:

$$4114\times 10{,}000\times 200\ \ RMB = 8.2\ \ bil\ \ RMB.$$

Similarly, one can figure out the budget for 2021, taking the yearly consumption of pork in 2020 as the starting level for 2021.

For simplicity, we let the subsidies roll out evenly over quarters, so that the price reduction is realized linearly. For example, in case 1 where all subsidies are spent on hog farms, the price falls to 32.0 RMB per kilogram by the end of 2020. Because the price only starts to fall in the third quarter of 2020, the prices in quarter 3 and quarter 4 are 38.5 and 32.0 RMB per kilogram, respectively. Similarly, the price falls to 22.4 by the end of 2021. With a linear reduction, prices are 29.6, 27.2, and 24.8 RMB per kilogram from quarter 1 to quarter 3 of 2021, respectively.

Following a similar procedure, one can calculate the number of chicken farms needed to achieve the same price reduction and the budget needed for subsidizing those chicken farms. We also assume that the increase in chicken supply comes evenly over quarters. For example, if spending half of the all-hog 2020 budget on chicken farms, the first increment of chicken supply arrives in the market in the first quarter of 2020. The same amount of increment continues in the next three quarters of 2020.

Fixing the ultimate goal of reducing the pork price to 22.4 RMB per kilogram and given a specific 2020 year-end price, we find the 2021 budget under a particular split of the all-hog 2020 budget. For example, if spending 50% of the 2020 budget on chicken farms, the price of pork already falls to 29.8 RMB per kilogram by the end of 2020. Thus, only 82% of the all-hog 2021 budget is needed to push the pork price further down to 22.4 RMB by the end of 2021. As much as 10.9% of the government expenditure, or 1.9 billion RMB can be saved over the 30-month window.

To quantify policy impacts on consumer welfare, which is the initial motivation for the government to subsidize hog production, we compute the consumer surplus (CS) from consuming pork based on the IAIDS model. Given equation (1), we write the price of meat i as a function of quantities, taking the expenditure ($E=\sum_{i=1}^{4}p_iq_i$) and $\ln(Q)$ as given (Cornes, 1992):

$$p_i=\frac{E}{q_i}\left(c_i+\sum_{j=1}^{4}\gamma_{ji}\ln(q_j)+\beta_i\ln(Q)+a_i^{'}t+b_i^{'}t^2\right)$$

Initially, we estimated the first-differenced IAIDS model and obtained estimated γ_{ji}, β_i, a_i, and b_i. Coefficients of t and t^2 are readily computed from estimated a_i and b_i. To back out c_i, we plug in these estimates into the equation(1):

$$c_i=w_i-\sum_{j=1}^{4}\gamma_{ji}\ln(q_j)-\beta_i\ln(Q)-a_it-b_it^2.$$

Next, we express the CS by taking the integral of price i over quantity i where superscript * indicates an equilibrium value in a particular year and superscript ˆ refers to the estimated coefficients:

$$CS_i=\int_0^{q_i^*}p_i(q_i)dq_i-p_i^*q_i^*$$

$$=\left[E\ln(q_i)\left(\widehat{c}_i+\sum_{j\neq i}^{4}\widehat{\gamma}_{ji}\ln(q_j)+\widehat{\beta}_i\ln(Q)+\widehat{a}_it+\widehat{b}_it^2\right)+\frac{E\widehat{\gamma}_{ii}}{2}(\ln(q_i))^2\right]-p_i^*q_i^*.$$

By fixing the coefficients at their 2018 values (see Table 2), we find prices and quantities under alternative policies and compute the CS for pork consumers in 2020 and 2021. Note that we only consider annual average prices and quantities in computing CS. We update E and $\ln(Q)$ in 2021 given the new equilibrium prices and quantities consumed under each policy. The estimated CS does not incorporate incremental surplus from enjoying reductions of pork prices earlier. With the conservative estimation of CS increase in cases 2 to 5 of Table 4, we see a nonlinear relationship between CS and the share of subsidies on chicken farms. More computation steps are available upon request.

Table A6
Baseline simulation parameters.

Parameter	Value	Unit
Year-end pork consumption 2019	4444.3	10,000 MT
Year-end chicken consumption 2019	2307.2	10,000 MT
Second half-year pork consumption 2019	1898.9	10,000 MT
Second half-year pork price 2019	44.9	RMB per kilogram
Target pork price by the end of 2020	32.0	RMB per kilogram
Target pork price by the end of 2021	22.4	RMB per kilogram
Yearly output per hog farm subsidized	10,000	heads
Yearly output per chicken farm subsidized	720,000	heads
Days of hog production cycle	180	days
Days of chicken production cycle	50	days
Subsidies per new hog farm	2.0	Million RMB
Subsidies per new chicken farm	0.4	Million RMB
Carcass weight per hog	78.0	Kilograms
Carcass weight per chicken	1.5	Kilograms

Notes: The subsidy on a chicken farm accounts for 8% of construction and yearly operational costs. *Yearly output per chicken farm subsidized* is computed as $360/50 \times 100,000$ where 360 is the number of working days of a year and 50 is the production days for nursery and growing chickens.
Source: Same as table 3.

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