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Abstract

The outbreak of African swine fever (ASF) in China has significantly reduced the country's pig production capability, whilst also having far-reaching impacts on livestock products supply in the wider food system. Previous studies have quantified the potential long-term impacts on food prices, however, little information is available regarding the direct short-term impacts on food system changes (livestock products supply and consumption patterns) and water quality protection associated with the outbreak. Here, we used multiple sources of data in relation to consumption patterns and water quality to fill this knowledge gap. Our results indicate that the ASF outbreak has changed the short-term livestock products consumption pattern in China, with increasing reliance on importation of livestock products. A rapid change in pork self-sufficiency rate has also driven a rapid increase in the consumer price index of many cities. Banned swill feeding and reversed environmental regulations in the watercourse intense regions has unintended consequences, especially on water quality. Swill, which is no longer fed, was dumped into water waste streams and lowered the sewage treatment efficiency. The re-establishment of pig production back into watercourse intense regions has led to exceedance of local manure nutrient loading capacity of agricultural land. We suggest (a) a short-term intermediate policy to prohibit discharge of swill to sewage systems, to return their previous efficiency, (b) the development of new technologies for the safe recycling of swills, and (c) the design of a long-term intelligent spatial planning of pig production, slaughter and transportation within China to ensure continued protection of water quality vulnerable zones.

1. Introduction

The African swine fever (ASF) outbreak in China, since August 2018, has reduced pig production by 22% in 2019 when compared to 2017 data (NBSC 2020). Although this decrease is less than the 50%–70% reductions reported by some media (Gu and Daly 2019, Pan 2019), it still has resulted in a significant reduction of the domestic pork supply. In addition, there has been a reduction of pig production due to tightening environmental regulations since 2014 (Bai *et al* 2019a). Previous studies have estimated that the potential long-term effects of ASF are increases in the global pork prices by 17%–85%, and increases in the prices of beef and poultry, as

animal-source protein alternatives, by 1.5%–6.7% in 2050, if there is not a full recovery of pig production in China (Mason-D'Croz *et al* 2020). The ASF outbreak in China may indirectly also increase pig production in other parts of the world; it has been suggested that half of the amount of pork consumed by Chinese people in 2050 will have to be imported, if Chinese pig production capacity will not be restored fully (Mason-D'Croz *et al* 2020, Tian and Cramon-Taubadel 2020). Although the ASF outbreak sparked a lot of interest regarding its impacts on food prices, food importation and pig production (Zhou *et al* 2018), none of the studies systematically reported the direct and short-term effects of ASF on China's livestock products consumption pattern and

importation, regional pork self-sufficiency nor consumer price index (CPI). Understanding these short-term impacts will assist policy makers to enact more promising interventions when faced with nationwide animal epidemics in the future.

The ASF outbreak has also direct and indirect impacts on surface water quality. China's water pollution problems are known to be both serious and widespread. Nitrogen (N), and phosphorus (P) losses along with chemical oxygen demand (COD) from sewage and agriculture, especially from intensive livestock production, are the main contributors to water pollution (Chen *et al* 2016, Han *et al* 2016, Yu *et al* 2019). The central government has implemented several regulations, notably since 2015, to combat water pollution at significant cost. They include relocating livestock production and increasing sewage treatment capacity. As a result, improvements in water quality have been observed in related regions (Ministry of Ecology and Environment (MOEE) 2018). The outbreak of ASF, in August 2018, may initially have contributed to an improvement in surface water quality associated with a reduction in pig numbers. However, the side-effects of ASF and its control measures have created a counterintuitive effect, where ASF related policies have subsequently worsen water quality in many parts of China. For example, the strict prohibition of swill feeding to control the risk of ASF viral spread, has meant that kitchen waste has no viable use and thus has increased pressure on sewage treatment plants (Zhao 2019). The discharge of oily food waste has lowered the sewage plant treatment efficiency, especially in popular tourist spots with a high proportion of kitchen waste from restaurants. These effects are not well reported and understood.

Here, we used the most recent updated statistical data from multiple sources to evaluate the short-term direct impacts of ASF and related control policies in China on domestic livestock products supply, the CPI, and on surface water quality. We propose two steps to be able to ensure that the detrimental impact of the ASF outbreak on China's pig production is not further exacerbated by unintended consequences reducing water quality by ASF control policies.

2. Materials and methods

2.1. Data collection

We collected and compared information about livestock production, trade, prices of different livestock products, CPI, and on water pollution between 2017 and 2019, with the ASF case first reported in Jilin province in August 2018. ASF was still prevalent in a few Chinese provinces in 2020, however, the outbreak of COVID-19 posed a greater threat on China's livestock products supply and environmental protection, so data from 2020 was excluded from our study so as not to conflate the impact of

the ASF outbreak with that of COVID-19. Another reason is that data for 2020 was not complete and available.

Data was collected from multiple sources, including data from National Animal Husbandry System, Ministry of Agricultural and Rural Affairs, Ministry of Ecology and Environment, and from the National Bureau of Statistic. The National Animal Husbandry System (www.nahs.org.cn/) provides information about livestock production, pig production cost, farm income and average slaughter weight of pigs, derived from the monitoring of 8000 pig farms (table 1). The selection and monitoring of these farms are performed by Ministry of Agricultural and Rural Affairs (MOARA), and only few monitoring results were open to the public (www.nahs.org.cn/). MOARA provided information about import of crop and livestock products at the national and provincial level, and wholesale prices of different livestock products at the farm gate (table 1). Water quality data of different monitoring sites alongside the Yangtze and Pearl River in 2018 and 2019 was provided by the Ministry of Ecology and Environment (table 1). Information about CPI at city and provincial levels was obtained from the National Bureau of Statistics (table 1). The data sources and links of each figure have been provided in table 1.

2.2. Calculation of main indicators

2.2.1. Pork self-sufficiency rate

The self-sufficiency rate (SSR) of pork was defined at provincial level, as total pork production divided by total pork consumption

$$\text{SSR} = \frac{\text{total pork production}}{(\text{average pork consumption}_{\text{per capita}} \times \text{population} / P_{\text{production to consumption}})} \times 100\%. \quad (1)$$

Here, SSR is the self-sufficiency rate at the provincial level, in %; average pork consumption_{per capita} is the amount of pork consumed at home per capita, which was derived from NBSC (2020), in kg capita⁻¹; population is the human population at provincial level, derived from NBSC (2020); $P_{\text{production to consumption}}$ is the fraction of the carcass weight that is actually consumed, which considered losses in the deliver chain and consumption in the restaurants, which was around 70% in 2015 in China (Ma *et al* 2019); total pork production at the provincial level was derived directly from statistic yearbook (NBSC 2020), in kg.

2.3. Manure nitrogen and phosphorus loading capacities

We also quantified the manure N and P loading capacities in the major provinces in Yangtze River Basin and Pearl River Basin, using the county level based

Table 1. List of data sources used in this study with links to the websites.

Figures	Item	Sources	Links
Figure 1(a)	Livestock production Livestock trade	National Animal Husbandry System Ministry of Agricultural and Rural Affairs	www.nahs.org.cn/ http://zdscxx.moa.gov.cn:8080/misportal/public/agricultureIndexRedStyle.jsp
Figure 1(b)	Contribution to urban CPI	National Bureau of Statistics; International Pig Industry press	www.stats.gov.cn/
Figure 1(c)	Prices of chicken, egg, beef, pork and mutton Price of milk	Ministry of Agricultural and Rural Affairs Ministry of Agricultural and Rural Affairs	www.sohu.com/a/403565872_120051684 http://zdscxx.moa.gov.cn:8080/nyb/pc/index.jsp
Figure 1(d)	Economic losses	National Animal Husbandry System	http://zdscxx.moa.gov.cn:8080/misportal/public/agricultureIndexRedStyle.jsp
Figures 2(a)–(g)	Provincial level import	Ministry of Agricultural and Rural Affairs	http://xmy.agri.cn/Default.aspx
Figures 2(h)–(n)	City level CPI	National Bureau of Statistic	http://zdscxx.moa.gov.cn:8080/nyb/pc/index.jsp
Figures 3(a)–(i)	Water pollution data	Ministry of Ecology and Environ- ment	http://data.stats.gov.cn/easyquery.htm?cn=C01 www.mee.gov.cn/hjzl/shj/dbsszyb/
Figures 3(j)–(m)	Manure loading capacity	NUFER county model	Chen <i>et al</i> (2019)
Figure 3(n)	Population, tourism	National Bureau of Statistic	http://data.stats.gov.cn/easyquery.htm?cn=C01
Figure 4	Water quality in Lijiang	Corresponding author	Corresponding author and local government report.
Figure S1 (available online at stacks.iop.org/ERL/16/054032/mmedia)	Import of crop products	Ministry of Agricultural and Rural Affairs	http://zdscxx.moa.gov.cn:8080/misportal/public/agricultureIndexRedStyle.jsp
Figure S2	Average slaughter weight of pigs	National Animal Husbandry System	http://xmy.agri.cn/Default.aspx
Figure S3	Price and cost of pork	National Animal Husbandry System	http://xmy.agri.cn/Default.aspx

NUtrient flows in Food chains, Environment Resources use (NUFER) model (Chen *et al* 2019). The NUFER model quantifies N and P flows through food systems at the county, provincial and national level. The NUFER-county model covers 2300 counties (including districts in the urban area). The model comprises an input module, a calculation module and an output module. It is a steady state model, and can be used to analyze nutrient flows through food chains for different time series (Chen *et al* 2019).

We define manure N (or P) loading capacities at county level as the ratio between total N (or P) excretion in manure and total crop N (or P) uptake. This is an indicator to evaluate the manure N (or P) loading, and not the actual N (or P) surpluses at the county level. Hence, other sources of N (or P) inputs were excluded in the calculations. A low manure loading refers to a low manure N (or P) excretion relative to the amounts of N (or P) in the harvested crop within a county. A high manure loading ratio refers to a manure N (or P) surplus within a county (Jin *et al* 2020). The county level results were downscaled to grid cell. Land use data on $1\text{ km} \times 1\text{ km}$ grids were provided by the Data Center for Resources and Environmental Sciences (www.resdc.cn), and were used to explore the spatial distributions of crop production and livestock production. Livestock production was evenly allocated to rural settlement areas in each county. To reduce small-scale uncertainties, the resulting 1 km^2 grid maps were aggregated to 5 km^2 grid resolution (Zhao *et al* 2017).

Year-to-year changes of COD at national water quality monitoring points along the Yangtze and Pearl River Basins in June and July in 2018 and 2019 were derived from national water quality monitoring programs of the Ministry of Ecology and Environment (table 1). The period of June and July is the main tourist season in China, with peaks in visits to restaurants and discharges of during when people were crowded in the restaurant and created higher amount of kitchen waste. We selected 15 monitored sites along the Yangtze River and 12 sites along the Pearl River, for detail see supplementary information.

3. Results and discussion

3.1. Impacts on food system

Total reduction of pork production was 12.0 Mt, while the net import of pork increased by 0.80 Mt. Based on these data, we infer that the net consumption of pork was reduced by 11.2 Mt between 2017 and 2019. However, total consumption of other livestock products increased by 4.6 Mt for meat products (sum of chicken, beef and mutton), 2.1 Mt for eggs, 4.9 Mt for milk and 2.2 Mt for aquatic products during the same period (figure 1(a)). The increased consumption of other livestock products almost offset the decrease of pork consumption caused by ASF. Hence,

the animal-source food consumption changed; the consumption of pork decreased by 20%, while the consumption of chicken, beef and milk increased by 12%–19% when compared with in 2017. The increases in the consumption of chicken and milk were partially due to lower prices when compared to those of pork (figure 1(c)), and partially due to the consumers' concerns regarding pork safety in relation to ASF.

Around 70% of the increases in the consumption of beef, milk and aquatic products were coming from import (figure 1(a)). This increased import of livestock products may provide solutions for livestock products demand in the short-term. However, this may not be sustainable in the long-term, as various exporting countries are facing environmental challenges to meet international and national targets, especially in relation to ruminant products (Du *et al* 2018). Brazil, contributed 23% and 67% to China's beef and chicken imports in 2019, respectively (Ministry of Agricultural and Rural Affairs (MOARA) 2020), but livestock production in Brazil is under dispute due to the ongoing deforestation of the Amazon. It has been estimated that the beef export from Brazil is responsible for the deforestation of about 73 000 ha each year, and that China accounted for 22%–31% of all export-associated deforestation risk in Brazil (Zu Ermgassen *et al* 2020). Most of the imported pork was coming from Europe; however, pork production in Europe heavily relies on the import of soybean from Brazil, especially from regions with high deforestation risk (Escobar *et al* 2020). Further, Europe and New Zealand are the major exporters of pork and milk to China (Du *et al* 2018, Ministry of Agricultural and Rural Affairs (MOARA) 2020), but these countries are under pressure to reduce greenhouse gas emission from ruminant production, following the Paris Agreement. In addition, ruminant animals production has been implicated for ammonia emissions and nitrate leaching in Europe and New Zealand and large efforts are being made to reduce these N losses (Webb *et al* 2005, Dymond *et al* 2013, Backes *et al* 2016). As a consequence, increasing livestock production in Europe, New Zealand and Brazil for export to China is not without difficulties.

China's ASF outbreak appeared to have less impact on animal-feed consumption between 2018 and 2019, as the total import of soybean (*Glycine max*) was maintained at around 88 Mt (figure S1). However, the main exporter to China changed from the United States (US) to Brazil due to the trade dispute between China and US. The stable consumption of soybean, despite the pig production reduction, is partly related to the rapid increase in slaughter weight of pigs, as farms were pursuing higher profit per head of pig, which increased the feed consumption per kg of pork, as feed use efficiency decreases at the later growth stage of pigs (fattening) (figure S2), and partly due to the increase production

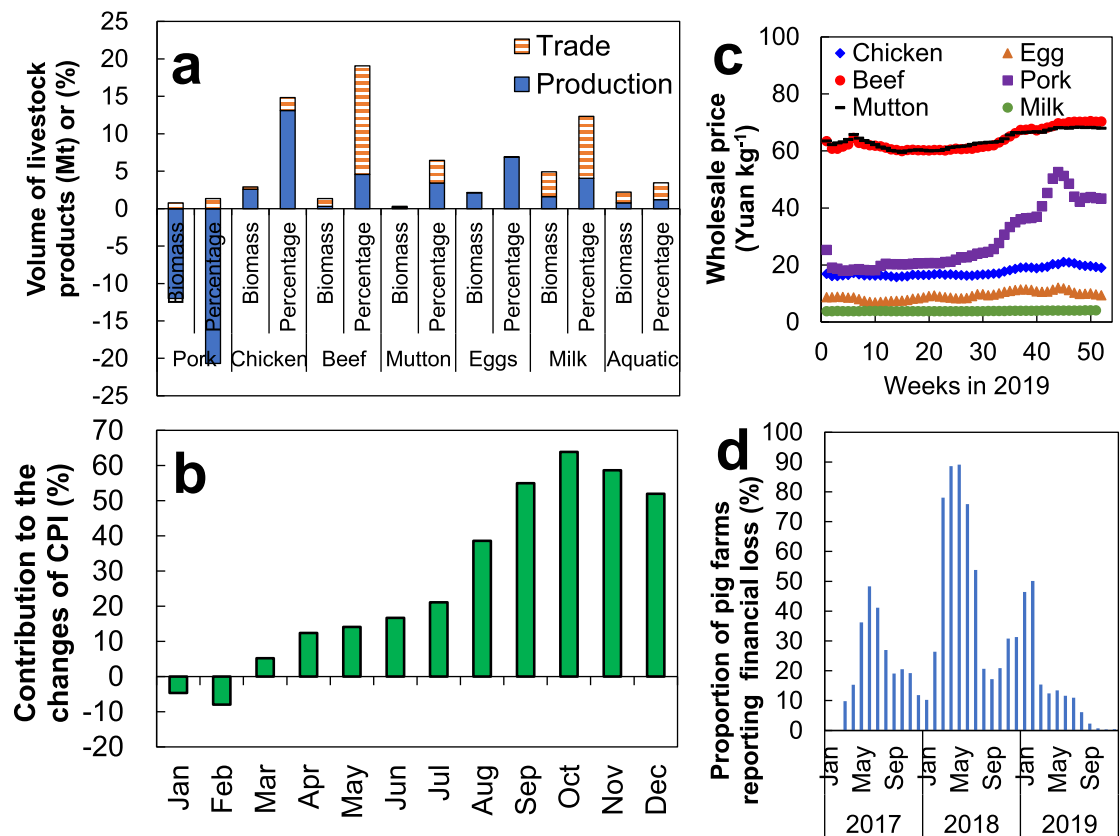


Figure 1. Changes of livestock products consumption between 2017 and 2019, in million ton (Mt) and in percentage of the consumption in 2017 (a), the contribution of pork price changes to the changes of consumer price index (CPI) of different months in 2019 (b), weekly changes of livestock products whole sale price in 2019 (c), and the proportion of farms reporting economic losses (based on monitoring data of 8000 long-term monitored industrial pig production farms) during 2017–2019 (d). Note: 7.0 Chinese Yuan equals about 1.0 US \$.

of other livestock species (figure 1(a)). The stable consumption of soybean may also be related to the ban on swill feeding; soybean and other relevant feed were used as substitute feeds.

3.2. Impacts of consumer price index

Outbreak of ASF has changed pork supply and demand at the regional level, such as in Shandong and Henan where SSR of pork was reduced by around 60% between 2017 and 2019 (figures 2(A) and (b)). The SSR of pork has been reduced to <22% in Zhejiang, Beijing and Shanghai, and <50% in Tianjin, Jiangsu, Fujian and Guangdong (figures 2(A) and (a)); where livestock production has been greatly reduced, due to the ASF outbreak and previous water and environment protection policies (Bai *et al* 2019a). Different provinces followed different strategies to ensure the stability of livestock products supply. For example, Beijing and Jiangsu relied more on domestic (trans-provincial) supply and the direct import from international markets was decreased between 2018 and 2019 (figures 2(A), (a), (d)). Beijing imports pork from Northeast China, and expanded its own pig production again in the peri-urban area, where many pig farms were shut down between 2015 and 2017, as a measure of the water

quality protection (Patton and Gu 2020). Shanghai, Zhejiang, Shandong and Tianjin were more reliant on international markets, for different products (figures 2(A), (b), (c), (e)). Similarly, these provinces also greatly expanded pig production around the urban area again, via new-build large scale pig farms. For example, a 12-store pig farm has been planned (Standaert 2020).

A shortage of pork led to an increase in the urban CPI for meat, in both the high and low pork SSR regions. The increases in CPI started in the middle of 2019 (figures 2(B), h–m). Urban CPI of all commodities increased by 3%–5% in major cities, with around 50% of the increase contributed by the increase in the price of pork, between September and December 2019 (figures 2(B), (h)–(m); figure 1(b)). The pork price has a heavy weight in China's CPI basket, and hence, pork price is commonly used as barometer for CPI in China (Ming 2013). The National Bureau of Statistics of China (NBSC) reported that the pork prices contributed more than two-third to the increases of CPI between January and October 2019 (NBSC 2019). Interestingly, some pig farms benefited from the ASF outbreak. More than 50% of the 8000 monitored industrial pig production farms were reporting loss of money (negative farm incomes)

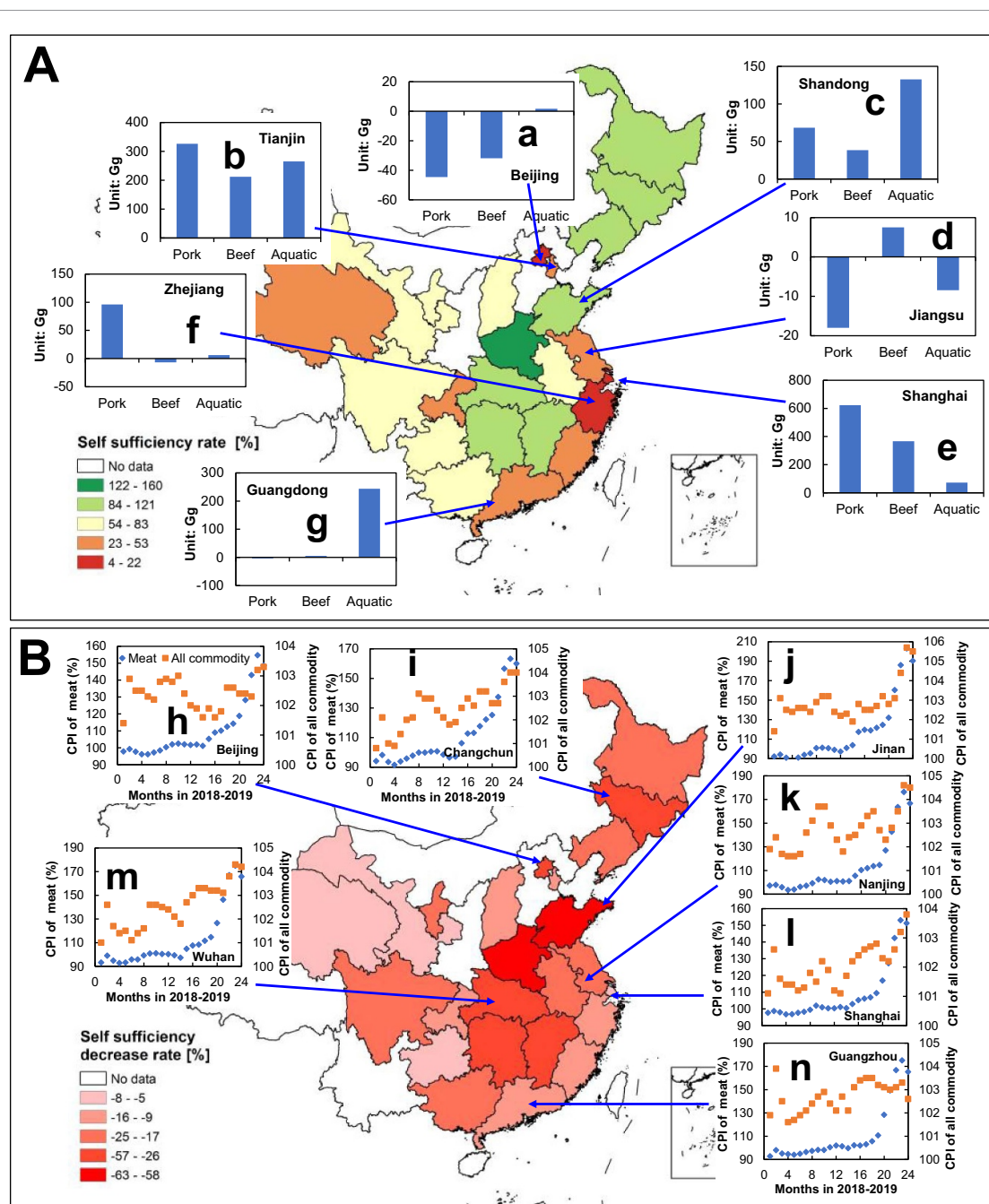


Figure 2. The self-sufficiency rate of pork in different provinces in 2019 (A), and decreases in self-sufficiency rate of pork between 2017 and 2019 (B). Bar charts show the changes in the import of main livestock products between 2018 and 2019 in Beijing (a), Tianjin (b), Shandong (c), Jiangsu (d), Shanghai (e), Zhejiang (f) and Guangdong (g). Line charts indicate the changes in consumer price index (CPI) for meat and all commodities in Beijing (h), Changchun (i), Jinan (j), Nanjing (k), Shanghai (l), Wuhan (m) and Guangzhou (n) during 2018 and 2019.

Note: consumer price index was calculated at the basis of previous year.

before ASF, and almost none of them were reporting financial loss after September 2019 (figure 1(d)), thanks to the increased whole sale price and stable production cost per kilo of pork (figure S3). However, there is no information about the proportion of farms that ceased the production following the ASF outbreak; the apparent positive effect of the ASF outbreak on the income of pig farms in 2019 may be biased because the number of farms that had to stop was not reported.

3.3. Impacts on water quality

The direct reduction in pig production as a result of the ASF outbreak likely resulted in a reduction in water pollution by as much as 0.44 Tg N and 0.16 Tg P, based on the average loss of 3.1 kg N and 1.1 kg P per head of pig in the whole pig production-consumption chain (Bai *et al* 2014), and the decrease in the number of pigs (144 million head) between 2017 and 2019 (NBSC 2020). However, the indirect (and somewhat 'hidden') environmental impacts of

the ASF outbreak may have worsen the water quality in many parts of China, where water pollution problems are both serious and widespread (Chen *et al* 2016, Yu *et al* 2019); the side-effects of the ASF outbreak and its control measures have created a counterintuitive effect.

In response to the outbreak of ASF, the central government implemented several new regulations to control the spread of virus at the beginning of 2019, such as culling infected pigs, banning the trans-provincial transport of live pigs from the infected regions, banning swill feeding, and enhancing bio-security management of pig production (Zhao 2019). The central government also enacted policies to recover pig production, when faced with large shortages of pork late 2019. These enabling policies included free use of arable land for construction of pig farms, cancellation of the restriction of a maximum of 1 ha for the construction area of livestock farms, cancellation of the need for pollutant discharge permits, and loosening of the regulations related to 'none-livestock production' regions (The State Council 2019a, 2019b). These pig production recovery policies aim to pull back or even cancel the environmental regulations that were enacted just several years ago.

A first unexpected effect of the ASF control measures is related to the prohibition of swill feeding, following the detection of ASF virus in kitchen wastes (Zhao 2019). China produces around 17–18 million tons of kitchen waste in urban regions each year, in part due to its thriving catering industry. These kitchen wastes are rich in protein, energy (fat and carbohydrate) and other essential nutrients for monogastric livestock, and they are commonly used as animal-feed in the pig industry. This practice has existed for thousands of years, and was a pillar of the industry prior to the outbreak of ASF in China. However, when the demand for swill by the pig feed industry was removed by the new legislation, kitchen wastes were increasingly discharged into sewage treatment systems or directly into watercourses, due to lack of alternative uses. Both unregulated discharge pathways have adverse effects on surface water quality.

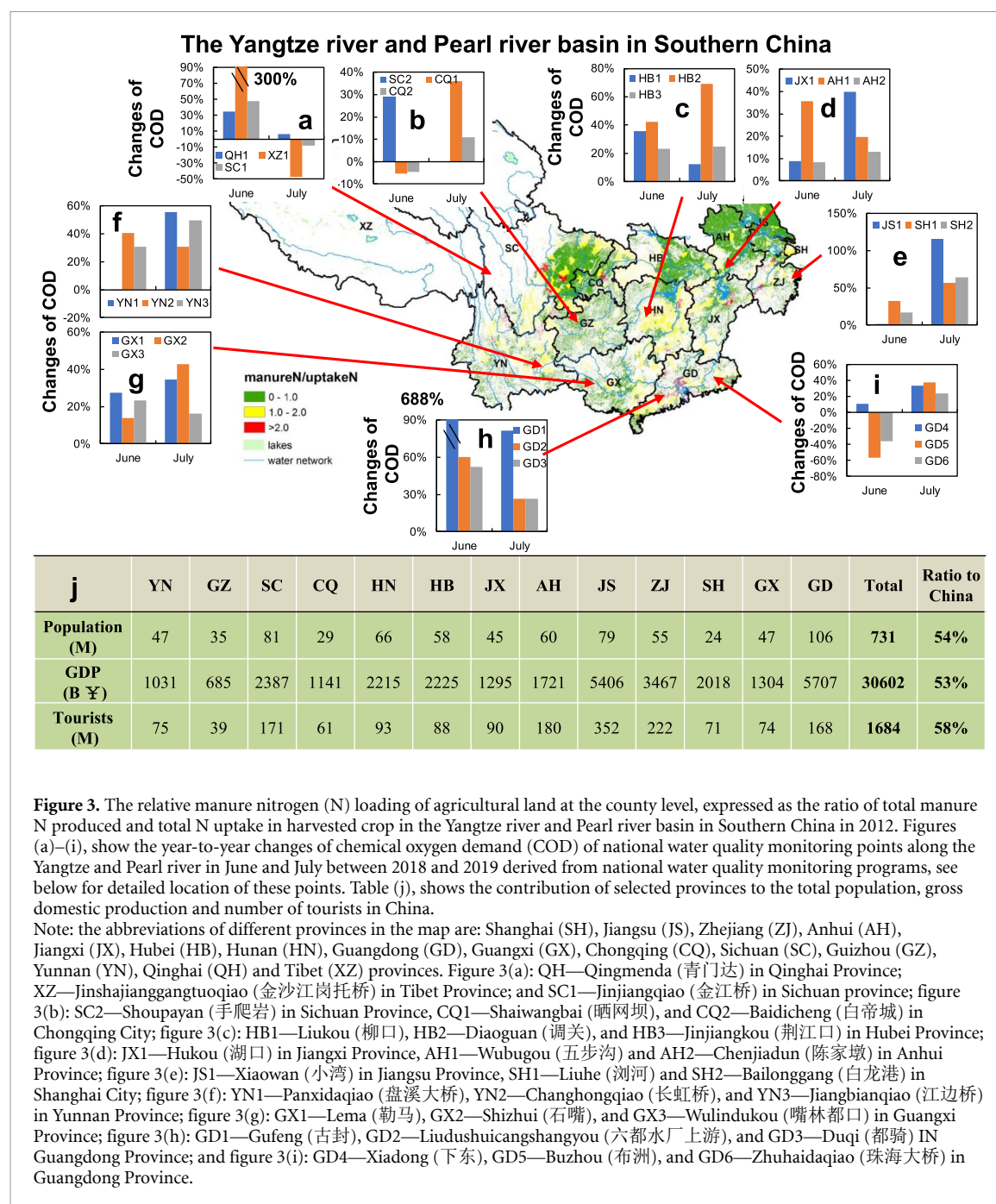
There were 4300 sewage water treatment plants in China, with a treatment capacity soaring to 70 billion $\text{m}^3 \text{yr}^{-1}$ in 2017 (Ministry of Ecology and Environment (MOEE) 2018, NBSC 2020). These treatment plants removed 10–20 Tg N and 51–102 Tg COD in 2017, which has contributed to the gradual improvement of China's surface water quality (Zhang *et al* 2016, CNEMC 2019). Most treatment plants use combinations of treatment techniques: physical-chemical techniques, oxidation ditches, anaerobic-anoxic-oxic treatment, and biological films, many of which highly rely on the activity of bacteria (Zhang *et al* 2016). However, kitchen wastes contain a high proportion of animal fats and vegetable oil, which

covers the surface of bacteria, may kill bacteria in the oxidation ditch, blocks the pores of filters, and slows down the physical-chemical treatment processes. Hence, the discharge of kitchen wastes has deteriorated the effectiveness of many sewage water treatment plants. This puts the achieved improvements in sewage water treatment at risk.

There were no public reports on changes in water quality following the implementation of ASF control policy measures. However, the COD of surface water along the Yangtze and Pearl rivers was much higher in June and July in 2019 compared with the COD in June and July of 2018, according to national water quality monitoring programs (figures 3(a)–(i)). These monitoring points are located near popular tourist cities and the high COD values were found in the peak tourist season (June and July), when population number and subsequent produced kitchen wastes in the cities were high (CNEMC 2019; figure 3(j)). This finding supports our hypothesis that ASF control policy measures may have increased surface water pollution through direct discharges of kitchen wastes into surface waters and through discharges of kitchen wastes into sewage treatment plants reducing the effectiveness of treatment (Pintor *et al* 2016, Zhang *et al* 2016). This is further supported through a case study in Lijiang city of Yunnan Province. Since June 2019, the oxidation pond of the sewage water treatment plant has been covered by a thick layer of oil and fat, which originated from kitchen and restaurant wastes. The oil and fat had to be removed manually several times a day to allow treatment to occur. Despite the attempt to remove the oil, the total N content of the effluent was still 3.2-fold higher in July 2019 than in July 2017, suggesting poor N removal in the water treatment plant (figure 4). Although the prohibition of swill feeding policy was implemented in November 2018, also in Yunnan Province where Lijiang is located, the observations of a significant increase of COD in April to July 2019, when the number of tourists visiting the city peaked, clearly indicate kitchen waste disposal to water courses.

3.4. Impacts on water quality protection policies

A further unexpected side-effect of the ASF control policies on water protection is related to the reversal of environmental regulations, so as to support the recovery of the pig production sector. In 2017, China implemented a national wide designation of 'none-livestock-production regions' (NLPRs). This policy set a red line and forced pig production to move out of regions with intense watercourses, where the water quality was sensitive to pollution by intensive pig production. The NLPRs policy directly caused a reduction in pig numbers by 46 million heads, and a shut-down of 0.26 million pig farms between 2014 and 2017 (Bai *et al* 2019b). Many provinces with watercourse intense regions saw a reduction in pig production by around 20%–50%,



which subsequently reduced the pork SSR in these regions (Bai *et al* 2019a). The central government also introduced a pollutant discharge permit plan, which fined livestock farms discharging pollutants to air and water. Implementation of these policies has encountered many conflicts, but local governments have resolutely implemented these policies to ensure protection of water quality in vulnerable zones at all cost.

However, when faced with a growing shortage of pork in the market, and subsequent surging pork prices due to the ASF outbreak, both the central and local governments were under great pressure to support the pork market. As a result, a series of policies

have been enacted to recover pig production. Despite promising results on water quality, because of the strict environmental regulations, the response to the ASF outbreak has resulted in many of these being loosened, to recover pig production in these regions. These pig production recovery policies aim to pull back or even cancel the environmental regulations that were enacted just several years ago. These loosened policies obstruct water quality improvements and water pollution control, especially in the watercourse intense regions.

Many provincial governments have replaced the 'livestock red zones' around water courses, which prohibited pig production to protect surface water



TN content in the Yanggonghe river (mg N L⁻¹)

	2017	2019
Jan	1.5	1.8
Feb	0.8	1.3
Mar	0.8	0.9
Apr	1.6	2.3
May	1.5	1.5
Jun	1.9	3.1
Jul	0.8	3.5

Figure 4. Floating oil and fat from kitchen wastes on the oxidation pond of a sewage treatment plant in Lijiang city, a tourism hot-spot in south China, following the implementation of the ASF control policy in 2019, which prohibited swill feeding to pigs. The table presents the mean total nitrogen (TN) concentration of the water in the adjacent river, which receives the effluents from the treatment plant, in 2017 and 2019.

quality, with a new smaller ‘red zone’. The new smaller ‘red zone’ is based on trying to achieve both protection of surface waters and guaranteeing minimum required pork SSR. In some of the watercourse-intense regions, including Sichuan, Jiangsu and Guangdong, the mayors of local city governments have been asked to keep the pork SSR at 70%–100% (The State Council 2019b). Although the reasons for the shift in policies in the face of the ASF outbreak are understandable, backtracking on previous successful environmental regulations have serious impacts on national water protection.

Basically, there is no capacity in the watercourse-intense regions (yellow and red regions—figures 3 and 5) to expand pig and livestock production, as the mean total manure N and P excretions by livestock at county levels are already higher than the potential mean N and P crop uptake in most counties (figures 5(b)–(d)). Moreover, the estimated manure N and P absorption capacity was likely overestimated, since it was assumed that the N and P crop needs at county levels could be covered by manure N and P, without considering the transportation cost for the redistribution of manure between livestock farms and crop farms. These costs can be high, especially in the hilly Southern China region, suggesting that adequate redistribution of manure within counties is not always feasible.

A high watercourse intensity in a region with red zones around these water courses means there is little land area suitable for livestock production, due to the need to keep livestock production away from watercourses. For example, Yancheng City in

Jiangsu Province has been evenly divided into squares by canals and rural residential houses. Both the width and length of the squares is not large enough to keep livestock farms far enough (>1.0 km) from rivers, canals and houses (figure S4). If we apply the standard red zone distance to rivers, canals and residential houses of >1.0 km, potentially, only <20% of the land may be used for pig farming in watercourse-intense regions (figure 5(e)). However, most of this land is protected cropland, leaving little room for new livestock farms.

3.5. Implications for policy

The mixed effects of ASF and now pressingly COVID-19, and their control policies, have led to an increase in the importation of livestock products and a change in consumption patterns of livestock products in China. The global external resource use and environmental impacts of China’s ASF need to be further explored, and pathways for more sustainable food import strategies need to be sought to secure sustainability of livestock products supply at the global scale. In addition, a rethink and redesign of ASF related policies are needed, to also protect water quality. There is need for immediate action and innovative thinking to develop pathways towards sustainable livestock production to achieve Sustainable Development Goals (SDGs) not only in China but globally. Below, we propose two steps to ensure that the detrimental impact of the ASF outbreak on China’s pig production is not further exacerbated by unintended consequences of ASF control policies.

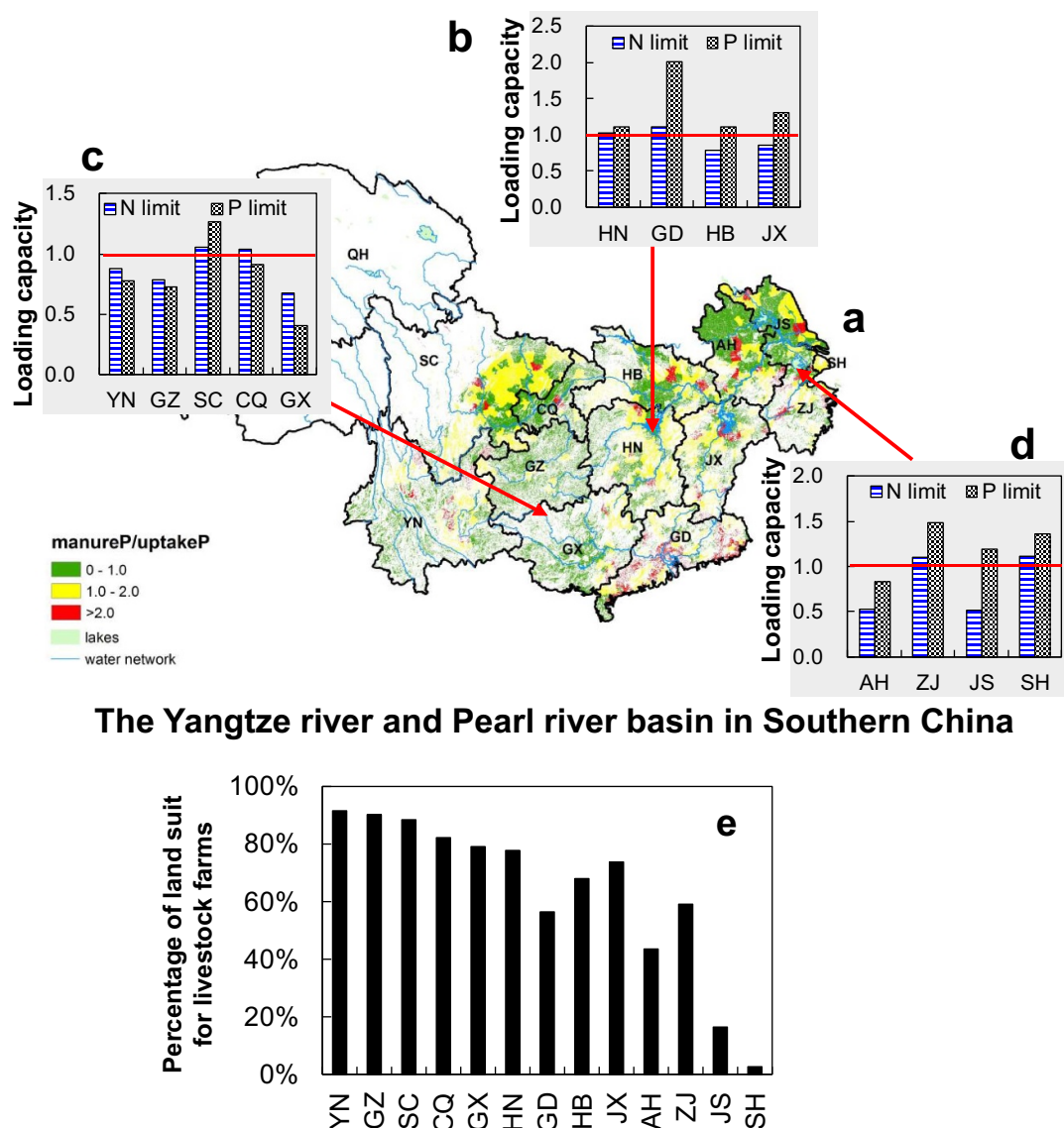


Figure 5. The map shows relative manure phosphorus (P) loading of agricultural land at the county level in the Yangtze river and Pearl river basin in Southern China in 2012 (a). Figures (b)–(d), show the capacity of livestock production and manure N and P loading at the provincial level from the upstream to the downstream of Yangtze and Pearl River basin based on NUFER county model. Figure (e), shows the percentage of area suitable for livestock production at the provincial level, considering the set minimal distance to the watercourses (>1.0 km).

Note: the higher the bar, the lower the remaining capacity, if the value is larger than 1.0, then there should be no expanding of livestock production in the given region. The abbreviations of different provinces show in the figure 3.

In the short-term, we propose two immediate actions. Firstly, a ban on the discharge of kitchen wastes from restaurants to water courses, to ensure that the sewage treatment plants capacity and efficiency is not detrimentally affected by oil and fat. To strengthen the implementation of this policy, a monitoring and penalty system should be built simultaneously to track and ban kitchen wastes discharges. Secondly, adjust the ASF control policy on swill feeding, to allow kitchen waste to be used again as animal feed or soil amendment (compost, digestates) following suitable treatment (Liu *et al* 2020). This involves the development of a track and trace whole-chain approach for production, collection, transportation, treatment and use of swill. Alternative

pathways for recycling kitchen wastes have to be explored as well (Liu *et al* 2016, Uwizye *et al* 2019).

In the long-term, China must develop and implement a sustainable spatial plan for pig production, to match with local manure nutrient loading capacity and fulfill multiple environmental related SDGs, related to air and water pollutions. The maximum pig production levels in watercourse-intense regions have to be set in relation to the N and P uptake in harvested crops in a region. Pig production farms should be relocated from regions with low manure nutrient loading capacity to regions with high manure loading capacity and low water pollution risks, while avoiding pollution swapping (e.g. ammonia emission). The locations of pig slaughter houses need to be

reconsidered as well, to reduce the transport distances associated biosecurity risks.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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