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Boom and Bust in China's Pig Sector during 2018–2021: Recent Recovery from the ASF Shocks and Longer-Term Sustainability Considerations

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Abstract: China's African swine fever (ASF) outbreaks, which started in 2018, severely damaged the country's pig and sow herds and created serious pork supply shortages. This resulted in high domestic market prices and record amounts of imports in both 2019 and 2020, but also severely impacted its domestic consumers. It casts doubts on whether China's long-standing self-sufficiency strategy, including its recently communicated 95% self-sufficiency target, can be sustained. Recent data, however, suggest that China is experiencing a rapid recovery in pig production, leading to depressed domestic market prices. This study characterizes the recovery process and analyzes the underlying drivers, such as active responses to the ASF outbreaks, a multiple-prong government initiative towards supporting the pig producers, de facto relaxations of newly introduced environmental regulations, large increases in domestic investment, and a reorganization of the pig sector, featuring more scale operations. However, the rapid recovery has also resulted in decreasing prices, economic losses of producers, and dampened export opportunities for China's trade partners. This paper, therefore, also analyzes these unintended consequences and explores supply-side measures that may enable the long-run viability of the self-sufficiency goal in the presence of high dependency on imported feed. Through a model-based numerical simulation analysis, we find that supply-side measures, such as yield improvement, can substantially reduce reliance on import feed but can only increase domestic pork production marginally, while technical efficiency improvement in pork production has the largest potential in boosting domestic pork production.

Keywords: African swine fever; pig production; China; sustainable development; self-sufficiency; computable general equilibrium model

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1. Introduction

Instability in agricultural commodity markets and extreme price fluctuations have long been a major concern for consumers, producers and policymakers and have attracted continuing research [1–8]. This is because sudden rises in prices reduce the real purchase power of consumers; in the case of staple food, rising prices can lead to increased hunger and poverty incidence, particularly in developing countries. Low commodity prices, on the other hand, can reduce the profitability of agricultural production and damage producer's incentives. Thus, governments have designed and applied various price stabilization instruments and programs to ensure the stability of agricultural markets and their long-term sustainable development, for example through buffer stocks, intervention prices, agricultural insurance, and income support programs. Despite these efforts, large swings in agricultural markets can still be observed.

One recent prominent example is the major decline in pig production and rising pork prices in China, the world's largest pork market, during the 2018–2020 period. Although the

outbreak of African swine fever (ASF) as the main culprit and the associated economic costs and impacts on the global pork market have been analyzed [9–11], the rapid recovery of the sector and the ensuing collapse of pork prices have so far not been studied in the current literature. This gap raises important analytical questions on why the recovery has been achieved so quickly, and more importantly, on the unexpected "side effects" of the rapid recovery in both the short and medium terms. In the short term, market supply has quickly exceeded demand, leading to collapsed domestic market prices and resulting in widespread economic losses for producers. In the medium term, sustained losses could lead to the exit of producers from the sector, potentially causing another downward cycle, thus, impeding the sustainable long-term development of the sector. More generally, as a sector that is heavily dependent on imported feed (particularly soybean and maize) and that is operating at an overall lower efficiency, its long-term sustainability in supplying enough pork to the vast market of China ultimately rests on technological development and efficiency improvement [12,13]. Government initiatives that supported the recent recovery do not necessarily address this fundamental consideration.

Recent studies in the literature have either focused on the impacts of the ASF outbreaks on China's pig sector and the efficacy of government policy responses [11,14,15], or on its wider impacts on China's national economy [9] and the world economy [10]. In addition, the environmental impacts of reduced pig production have also been investigated [16]. However, these studies generally do not address factors underlying the quick recovery and the ensuing market and price movements. Studies [12,13,17,18] addressing the long-term prospects of China's pig sector are often outdated in respect to the new situation in connection with the ASF outbreaks and China's rising imports, thus, ignoring these vulnerabilities in China's pig sector. In light of these analytical gaps, the current study offers a timely empirical analysis rooted in economic theory and method to address the research gaps identified above for purposes of generating new insights into enhancing the sustainable development of the pig sector in China. Specifically, we first provide a qualitative analysis to account for the economic factors that have led to the sharp downturn and the ensuing quick recovery of China's pig sector and discuss the market effects of this dramatic cycle. Secondly, as the sector is mired in another potential downturn in a very short period of time, we apply a formal economic simulation model to quantify the domestic and world market effects of a set of supply-side measures that can potentially enhance the sector's long-term capacity.

The paper is organized as follows. Section 2 provides an overview of the recent development of China's pig sector and pork market. Section 3 describes the methodology applied in this study. Section 4 offers a qualitative analysis on the first research question, whereas Section 5 provides a model-based numerical analysis to answer the second research question. The last section summarizes the main findings of this study and provides a discussion on the policy implications of our findings.

2. China's Pig Production and Pork Market during 2000–2021

Pork is the most important meat choice of most Chinese consumers and the country is the world's largest producer and consumer of pork. The country's pork production increased from 39.7 million tons (46.8% of total world production) in 2000, to the highest level of 58.2 million tons in 2014 (52.2% of world total), before leveling off thereafter [19]. On the consumption side, China's domestic demand (which increased at an average annualized rate of about 3% during 2000–2015) had been largely met with domestic production up until 2015, implying nearly total self-sufficiency. Total consumption peaked at 58.7 million tons in 2014 (about 53% of total world consumption), followed by a small decline thereafter. As domestic production largely tracked the rising domestic demand, China's pork imports and exports were quite modest during the 2000–2015 period. On the export side, less than 0.5% of China's production were exported in recent years, mainly to its Hong Kong Special Administrative Region. On the import side, until 2015, less than 2% of China's domestic consumption were imports; however, from 2011, China's imports exceeded one-tenth of

total world trade and reached the level of 15% in 2015. Overall, China nearly maintained total self-sufficiency until 2015.

Domestic production started to level off from the highest level of 58.2 million tons in 2014, triggered by shrinking pig and sow herds since late 2013. Against much more stable domestic consumption, large amounts of imports exceeding one million tons first occurred in 2016 and continued well into the first 9 months of 2021. China's pork imports as a share of its total consumption doubled between 2015 and 2016 (i.e., from 1.7% to 3.6%) and then rose to double digits in 2020. The recent import surge was aided by the ASF outbreaks, which led to only 42.6 million tons of pork production in 2019, roughly matching the country's production in the early 2000s.

The deterioration of China's pork self-sufficiency ratio, even before the ASF outbreaks, is not totally unexpected, as domestic supply has suffered from higher production costs and lower profitability [14]. Tightened environmental regulations have also resulted in the abandonment of pig farming in areas where such regulations are enforced [20]. In August 2018, when the ASF outbreak was first reported, China's sow herd had already dipped to 31 million heads, about 40% lower than the peak level observed six years earlier (Figure 1). The ASF outbreaks accelerated this downturn. As shown in Figure 1, around September 2019, China's pig and sow herds dropped to 190 million and 19 million, respectively, the lowest levels in recent memory, according to official statistics from China's Ministry of Agricultural and Rural Affairs (MARA) [21]. This creates a huge gap between domestic demand and supply, raising domestic market prices and opening up the opportunity for increased imports. Pork prices increased from around CNY20/kg at the end of 2018 to the highest level of CNY56/kg in October 2019, before hovering around CNY50/kg until January 2021 (Figure 2). In 2019 and 2020, China's pork imports surged to record levels (2 and 4.3 million tons), despite trade disputes with the US, which lowered China's imports from the latter country. Against the huge supply shortage, however, the record amount of imports (and the release of frozen pork from the national stockholding system) did little to quench the rising domestic price. As a result, consumer demand shrank considerably in both 2019 and 2020 to levels that had not been recorded since 2003.

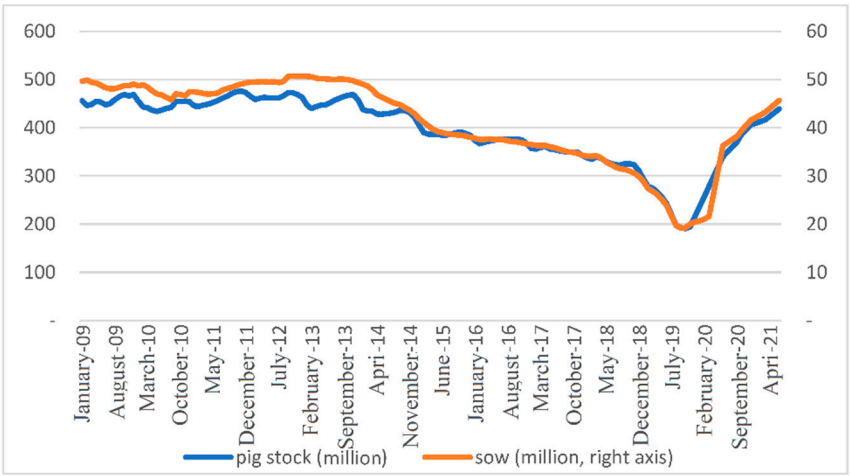

Figure 1. China's pig and sow herds: 2009–2021. Data source: www.gov.cn. (accessed on 16 January 2022).

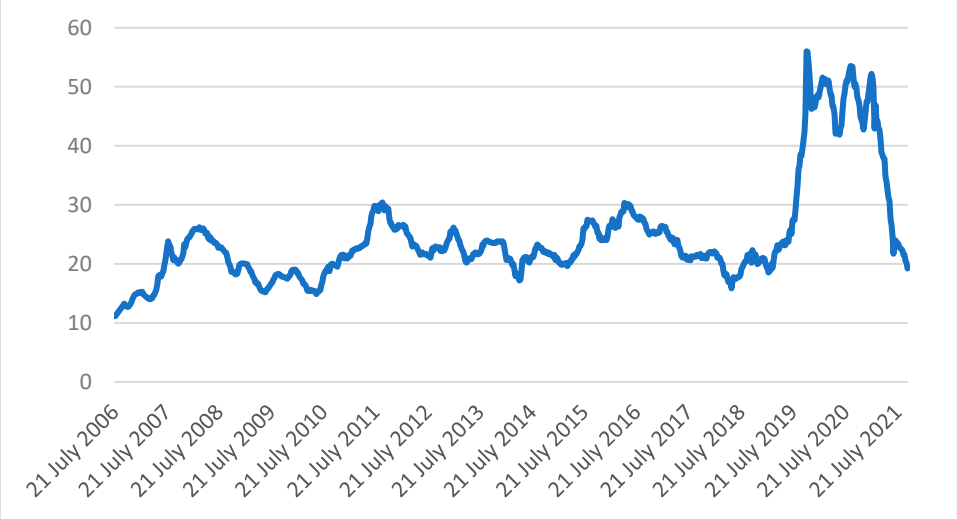

Figure 2. Average pork prices in China: 2006–2021 (CNY/kg). Data source: www.caaa.cn. (accessed on 16 January 2022).

In June 2020, 8 months after China's pig production hit the lowest point, production capacity in China's pig farms started to show robust signs of recovery, as pig and sow herds rose to the levels of 340 and 36 million heads, respectively. Following these developments, pigs delivered for slaughtering also rose sharply, resulting in a much improved supply (Figure 1). With the shrinking gap between pork demand and supply, China's domestic pork price has experienced a sustained decrease since February 2021, around the time that Chinese consumers stocked up pork for the Chinese New Year's holiday. The latest data for October 2021 show that market price all but receded to the pre-ASF levels (Figure 2). By the end of 2021, China's sow herd reached 43.3 million and total pork production in 2021 was nearly 53 million tons, approaching recent "norm" levels.

The restored production capacity and market supply is undoubtedly good news for Chinese consumers. However, the sudden swing of market prices has also spelled trouble for large and small producers alike, resulting in intensive discussions on how to manage the exit of excessive production capacities, and on what future scenarios await producers.

In response to these challenges, the Chinese government for the first time issued explicit guidance on the long-term development of the pig sector and on pork supply in 2020. In an official opinion issued by the State Council in September 2020 [22], a 95% self-sufficiency target for pork was proposed. In August 2021, together with several other government agencies, MARA [23] issued another official opinion on promoting "sustainable and healthy development of the pig sector", reiterating the 95% self-sufficiency targets. In light of the damages from the ASF crisis, this target reflects the central government's determination to restore the domestic supply capacity but falls short of the *de facto* total self-sufficiency observed prior to 2015, perhaps indicating a pragmatic recognition that total self-sufficiency is not achievable. However, the 95% self-sufficiency rate implies nearly three million tons of annual pork imports, assuming domestic demand stays close to the average annual levels before the ASF crisis. Questions also remain on whether the seemingly scaled back self-sufficiency ambition can be realized and sustained in the longer term, considering China's rising production costs, limited resource base for feed production, and trade policy "space" for limiting imports [17].

3. Methods

3.1. Qualitative Analysis

To answer the first research question posed in this study, we offer a qualitative analysis to explain the main drivers underlying the rapid recovery but also leading to the subsequent collapse of market prices. Based on up-to-date policy information that has so far not been

detailed in the literature, this qualitative analysis is rooted in an analytical framework of agricultural production function defined on multiple inputs. More specifically, pig farmers use various primary production factors, such as physical capital including building and farm machinery (denoted as K), sow (S), land (T), labor (L), purchased inputs, such as feed (f), and other inputs, such as energy and veterinary medicine (X), to produce pigs. We denote pig outputs as Y, defined by the following equation:

$$Y = A * F(K, S, L, T, f, X) \quad (1)$$

where the function F is increasing in each factor/input, holding constant all other factors/inputs, and the coefficient A is a productivity variable that measures the productivity level for a given combination of production factors and inputs. In the agricultural economic literature, specific functional forms, such as Leontief, Cobb–Douglas, Translog, and constant elasticity of substitution (CES) are used to parameterize the production function. In large multiple-product partial or general equilibrium simulation models, multiple level nested production functions are often specified to capture the differential substitutability of different inputs. For instance, in the well-known GTAP model [24], the output level Y is produced in a Leontief production function, combining individual purchased inputs and a value-added composite, the latter of which is produced through a CES function with individual primary factors, such as K, L and T.

To increase the output level Y, it is necessary to increase the productivity level and/or increase factors and inputs used. Note that production factors such as physical capital (K) and sow (S) are fixed in the short term for individual farms, as it takes time to build up additional capacity. Therefore, when adverse events, such as ASF or other animal disease, lead to reduced sow herd, the negative impact on pig production cannot be alleviated immediately, potentially resulting in prolonged production disruption. Moreover, in the short-term, there are very limited possibilities to substitute other factors and inputs for reproductive sows for purposes of increasing pig production, leading to a situation where the level of production would fall in proportion to the reduction in the sow herd. When the sow herd continues at a lower level, idled physical capital, land, and labor would eventually exit the pig sector. In turn, this makes it harder for the pig sector to return to normal capacity in the short term, even when the sow herd expands. Conversely, if overcapacity exists in the pig sector, for example due to government subsidies and other incentives, it would also take time to "downsize" the capacity by reducing sow herd and for other production factors to exit the sector. During the adjustment period, overcapacity can result in excessive supply that may depress market prices and lead to losses for producers.

To restore the production capacity to the pre-ASF level, it is, therefore, crucial to prevent further decline in sow herds through effective ASF containment and to provide incentives for farmers to rebuild their sow herd. At the same time, complementary measures are also needed to facilitate the inflow of other production factors, such as capital, land, and labor. However, as pointed out earlier, excessive public assistance and private investment can result in overcapacity in the next period, paving the way for another wave of price fluctuations. In the qualitative analysis in Section 4 of this study, we follow this analytical framework to describe key government initiatives and structure changes that supported the recovery process and also discuss the aftermath of the rapid recovery.

3.2. Quantitative Analysis

Several long-term weaknesses in China's pig sector can hinder its future development, making it susceptible to future supply shocks. One particular weakness lies in the reliance on imported feed grains and oilseeds, particularly soybean and maize [13,17,18]. For instance, China's soybean imports exceeded 100 million tons in 2020, more than 5 times China's domestic production (Figure 3). This dependency has raised serious concerns on potential feed supply risks, such as those related to trade conflicts with major supplying countries. Another concern is about the pig sector's substandard feed conversion ratio and overall (in)efficiency [12,18], which lead to higher costs and contribute to the declining com-

petitiveness of China's pork production, relative to imports. Potential supply-side measures to ensure the 95% pork self-sufficiency ratio may lie in the reduced reliance on imported feed grains and oilseeds, more efficient feed use, and improved technical efficiencies.

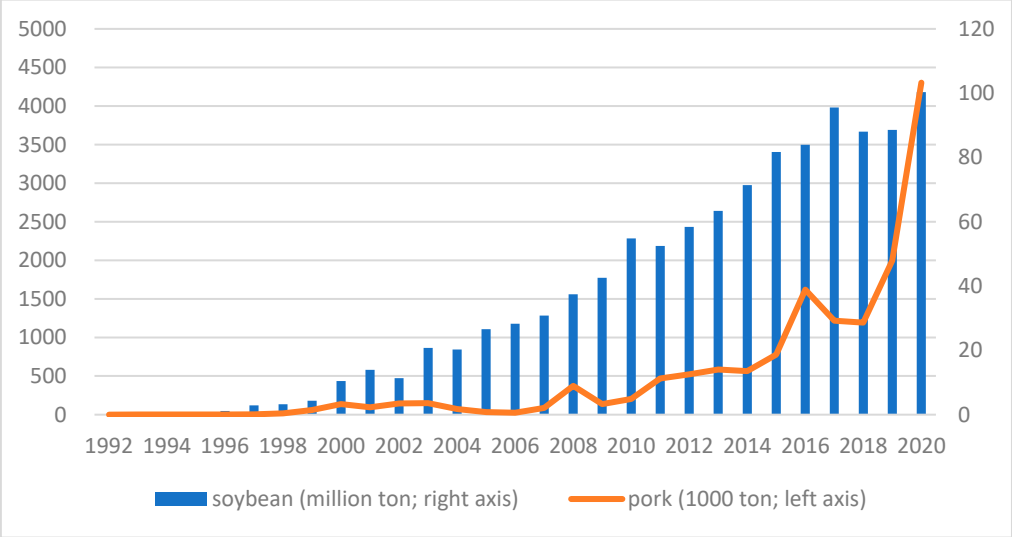

Figure 3. China's soybean and pork imports during 1992–2020 (source: UNCOMTRADE).

To answer the second question on strengthening the pig sector's long-term supply capacity, we use a quantitative economic model to simulate the potential impacts of the supply-side measures identified in the literature. To capture the extensive inter-sectoral linkages between feed and pig (and other livestock sectors) through intermediate uses and competitions for sources such as land, a multi-sectoral model is desirable for this analysis. As international trade for both feed grains/oilseeds, pork, and other animal food products is of interest in this analysis, the model should also cover multi-countries, including China and its main trading partners. In short, these considerations point to the use of a multi-sectoral and multi-country economic model that can simulate the effects of the various scenarios mentioned above. We, therefore, adopt the GTAP model, which is considered a standard computable general equilibrium (CGE) model that is widely used for the analysis of global economic issues, such as international trade, the environment, and climate change [24]. The GTAP model assumes perfectly competitive markets and constant returns to scale technology. Nested production with Leontief and CES production functions are used so that final outputs can be produced with intermediate inputs (e.g., feed grains) and primary production factors, such as land, capital, skilled and unskilled labor and natural resources, which are conceptually similar to Equation (1). On the demand side, demand of a representative private household follows a constant difference in elasticity demand function that is calibrated to income and price elasticities from the literature. The GTAP model tracks bilateral trade flows, linking all countries and regions in the model. In the standard GTAP model, land allocation is governed by a constant elasticity of transformation frontier. The version of the GTAP model used in this study is a variant used in Clora et. al. [25]. Definitions of the scenarios to be simulated with the model and modeling results are detailed in Section 5.

4. What Drives the Rapid Recovery of Pig Production in China? A Qualitative Analysis

The speedy recovery of China's pig sector has been driven by several factors, ranging from active responses to prevent the further spread of the ASF and the containment of outbreaks (i.e., preventing further declines of S in Equation (1)), extraordinary policy measures supporting the recovery of the pig sector (i.e., increasing S), large private investment (i.e.,

increasing ***K*** and ***T***), and structure adjustment that resulted in increased production scale (i.e., promoting productivity progresses).

4.1. ASF Containment

The outbreak of the ASF in China was first reported in August 2018. Official statistics suggests that there have been 160 ASF outbreaks since 2018, resulting in 1,193,000 pigs being culled [26]. However, as pointed out by other studies, these numbers likely underestimate the true severities of the impacts of the outbreaks, because of under-reporting and abandonment of pig farming by smallholders that were not included in official statistics [9,10]. The aggregated national statistics also indicate a much larger reduction in both pig and sow stocks (Figure 1), which is likely due to more pig death, culling, and losses of sows. In fact, data from the MARA show that, by December 2018, China's total pig herd had already decreased by 4.8% on a year-to-year basis, and its sow herd had decreased even more (by 8.3%) [27].

When ASF appeared in China in August 2018, the MARA activated the emergency mechanism to counter the ASF spread, by implementing a flurry of containment measures (see Table 1), including monitoring and reporting protocols, restrictions on cross-province pig transportations, suspension of slaughtering in affected areas, strict quarantine of infected farms/areas, elevated disinfections and safe disposal of culling of infected pigs [28,29]. On 13 September 2018, the Ministry of Finance (MOF) and MARA [30] jointly issued a notice on offering financial compensations to pig farmers in connection with mandatory culling. Initially, farmers received a compensation of CNY800 per culled pig, similar to the compensation scheme adopted during the foot and mouth disease outbreaks. Later, the compensation was increased to CNY1,200 per pig to ensure smoother implementation of the containment measures. According to official statistics, ASF outbreaks were down to 63 outbreaks, resulting in 390,000 culled pigs; in the first 8 months of 2021, there were only 11 minor outbreaks that led to 2200 pigs being culled, suggesting that the ASF outbreaks had been brought under control.

Table 1. Major government initiatives in containing the ASF outbreaks.

Source		Document	Related Contents
10 August 2018	MARA	Notice on the prevention and control of ASF and strengthening the supervision of pig movement	Strengthen the risk management and control of the movement of pigs, strengthen the quarantine work on the origin and slaughter of pigs, strengthen the supervision and management of the slaughtering process of pigs, and strengthen the supervision and inspection of the circulation process.
31 August 2018	MARA	Notice on effectively strengthening the supervision of transporting pig and related products	Vehicles that transport all livestock and poultry, such as pigs, no longer enjoy the "green channel" policy for fresh agricultural products
13 September 2018	MOF and MARA	Notice on doing a good job in the Subsidy for the Compulsory Culling of ASF	Offering financial compensations to pig farmers in connections with involuntary culling. Initially, farmers received a compensation of CNY800 per culled pig, similar to the compensation scheme adopted during the foot and mouth disease outbreaks.

Sources: authors' compilation of publicly available government documents. See reference list. MARA: Ministry of Agricultural and Rural Affairs; MOF: Ministry of Finance.

4.2. Government Initiatives

Aside from the ASF containment measures, government agencies have been actively assisting in the recovery of the pig sector, having issued 19 major supporting measures that provide favorable conditions on land use, environmental impact assessment, and assess to credits to pig producers. These measures range from those initiated by MARA on directly assigning production targets to local governments, to joint initiatives from a number of ministries on supporting the expansion of farm infrastructure, provision of production bonuses and subsidies, favorable terms on land use, transportation, and finance, to specific measures supporting farms with scale operations (i.e., farms with at least 500 pigs). On 28 July 2021, the State Council decided to extend the supporting policies and prohibited the exercises of over-constraining environmental regulations. Furthermore, the State Council also announced a counter-cyclical mechanism to offer government assistance when production capacity drops below a certain threshold or when pig farmers suffer from large financial losses for three consecutive months.

China's rapid economic development has fueled rising demand for animal-sourced food products, which in turn placed considerable stress on the environment, not least due to soil and water pollutions [20,31]. This led to tightened environmental regulations on livestock and poultry production that have played a role in constraining the development of the sector. During the period of January 2014 to May 2018, a number of major policy documents, regulations, and guidelines concerning livestock and poultry regulations, and two environmental protection laws were issued (as summarized in Appendix A, Table A1). These regulations lay out specific rules on the prevention and management of pollutants from livestock and poultry production, specific zoning regulations on livestock and poultry farms and slaughtering facilities [32,33]. For instance, livestock operations already located within the non-production zones were required to be either closed or relocated by end of 2017 [34]. In administrative areas (e.g., counties) designated as the main pig production area, a production plan needs to be conceived and implemented so as to lay out both zones for pig production and zones where production is forbidden. In 2016, a technical guideline was issued to guide the planning of permitted and non-permitted zones [35]. In 2018, a new law introduced an environment protection tax on pig farms with scale operations. The introduction of these regulations, laws, and guidelines likely shrank China's pig herd, prior to the 2018 ASF outbreaks, as illustrated in Figure 1. In particular, the drive to be compliant with the new regulations led to significant cost hikes and exit of producers. Studies suggest that costs related to environmental protectioncan be as high as 40–50% of the total investment in setting up new pig production facilities [36,37]. The added costs were particularly onerous for smallholders, accelerating the exit of those producers with fewer than 50 pigs. During the period of 2007–2017, the number of pig producers with fewer than 50 pigs decreased from 80.1 million to 35.7 million (Figure 4). On aggregate, even though numbers of medium and large producers increased during the same period, nationwide production capacity still decreased.

To aid the recovery after the ASF outbreaks, several environmental regulations have been effectively relaxed. On 21 August 2019, the State Council abolished all local rules that are inconsistent with national laws and regulations regarding areas where pig farming is either prohibited or limited. In addition, the one-hectare limit placed on land used for constructing "auxiliary production facility" was also repealed. According to the Ministry of Ecology and Environment (MEE), from late 2019 to March 2020, the number of "no-pig" zones was reduced by 14,000. On 29 November 2019, the MEE and MARA [38] jointly decided to further relax the environmental assessment regulations on pig farms, allowing projects with less than 5000 pigs to skip the formal approval process; for larger projects with more than 5000 pigs, the approval processes will be further streamlined.

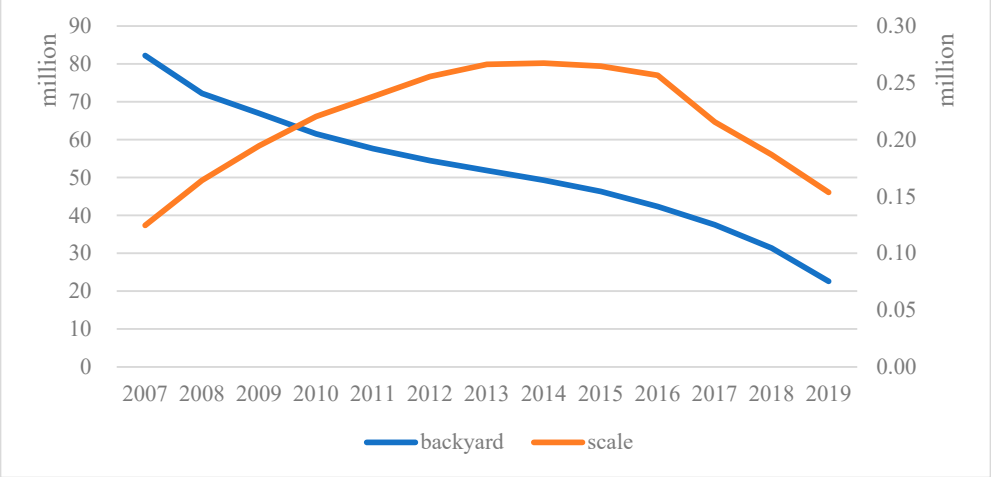

Figure 4. Numbers of pig farms with backyard operation (<50 pigs per farm) and scale operations (>50 pigs per farm). Source: China Animal Agricultural Year Books (various issues).

4.3. Investment and Structural Changes in China's Pig Sector

The persistently high prices during the ASF outbreak and the favorable credit, land use, and environmental policies attracted not only returning small producers but also large investors. On aggregate, the declining trend of small producers continues, resulting in rapid capacity recovery that is increasingly connected to rising production scales driven by large pig farms (Figure 4). In 2020, 57.1% of slaughtered pigs were from large farms with at least 500 pigs, as compared to 53% and 50.1% in 2019 and 2018, respectively [39].

These relatively large pig farms have played key roles in the recovery process. For instance, the top 9 corporate producers (including Muyan, Zhengbang, Wen's, New Hope Liuhe) delivered 10.3% of all slaughtered pigs in 2020, rising sharply from the share of 8.2% in 2019 and 6.9% in 2018. One of the driving forces behind the rapid expansion of the large farms is their ability to bear the costs related to the hygiene and biosecurity requirements in connection with ASF containment. In connection with their large operation scales, modern technologies adopted by large producers, such as better facilities and equipment, and farm management practices, allow these producers to be more productive. Access to credits and favorable land use and environmental assessment terms have also helped rapid recovery and expansions of sow and pig herds. Furthermore, some of the leading producers, such as Wen's, Muyuan, Aonong, and Tianbang, have invested in large vertical multi-storey breeding facilities to aid the expansion of their production scale. For example, a new pig facility by Muyuan can house 84,000 sows and produce 2.1 million pigs a year [40]. Last but not the least, these very large producers are increasingly engaged in operations that integrate sow breeding, pig production, feed production, and slaughtering. As shown in Appendix A Table A2, the top 9 largest producers in the country have all expanded their pig production during the 2016–2020 period and fully recovered any production losses suffered in 2019.

4.4. Aftermath of the Rapid Recovery

The rapid recovery of the domestic pig industry has greatly increased domestic pork supply, allowing consumers to resume their normal consumption levels at prices that are comparable to the pre-ASF levels (Figures 1 and 2). The fact that domestic market prices have dropped so quickly, however, also implies that producers may suffer from losses. Indeed, recent financial and news reports have suggested that many producers, including some of the largest corporate producers, incurred substantial losses in the third quarter of 2021. For some of the top producers, losses in the third quarter have negated the large profits realized in the first half of the year [41]. As market prices dipped below the average production costs, economic losses spread to the whole sector. In the fourth quarter of 2021, prices have somewhat rebounded; however, it is unlikely that the demand and

supply balance will tip into producers' favor anytime soon, given the peaking production capacity [42]. Therefore, the very success of the rapid recovery in fact reveals further vulnerability in China's pig industry that lies in the high production costs. While some producers may be able to withstand the near-term financial losses, others may have to exit the market. It is unclear how policy makers in China will deal with this new situation. Early indications suggest that they may continue to offer incentives for producers so that they do not exit amass to endanger the hard-fought recovery. Another wild card is whether the seemingly successful control of the ASF can be sustained so that larger outbreaks would not flare up again to cause another round of disturbance.

The rapid rise in Chinese imports of pork during the 2016–2020 period has made China the dominant customer on the world pork market, with imports reaching the levels of 4.3 million tons in 2020 and 2.9 million tons in the first 8 months of 2021. Several leading pork exporters, such as Spain, USA, Brazil, Denmark, Netherlands, and Canada, have all increased their exports during this period and benefited from the favorable prices there. The recent recovery of domestic pig production and pork outputs and falling domestic market price in China suggest that this trend is unlikely to continue in the short term. Looking ahead, further development of China's pig industry will continue to be an important part of China's drive to achieve its long-term goal of food and nutritional security, as indicated by the newly declared 95% pork self-sufficiency goal.

Realizing that this goal would still suggest nearly 3 million tons of imports annually, assuming that China's total consumption remains within the recent range of 54–58 million tons per year. Further increase in demand in China in the coming years may push imports to even higher level. Thus, in the longer-term, China would remain the most important export destination.

5. Supply-Side Measures and Future Scenarios: A Quantitative Assessment

5.1. Possible Supply-Side Measures in China's Feed Grain/Oilseeds and Pig Sectors

Feed costs and the availability of imported feed are fundamental determinants of the scale of pig production in China. The current literature suggests a large gap between actual and potential soybean and maize yields in China, pointing to the possibility of reducing feed import dependency. For instance, Liu et al. [43] analyze detailed county-level data and find that the average soybean yield in China is about 2 t/ha (ton/hectare), while the attainable yield is 2.98 t/ha. Similarly, the actual and attainable yields for maize are, respectively, 6.4 and 9.4 t/ha. Eliminating these yield gaps can, therefore, lead to very large output gains. In the same study, the authors also assess the economic and environmental benefits of reduced fertilizer uses per unit of outputs through integrated soil-crop system management. Regarding feed conversion ratios, the feed industry and government authorities have endorsed expert recommendations on reducing the protein contents of pig feed from the prevailing 16% to 14% so as to achieve reductions in the use and imports of feed grains and oilseeds, without affecting pig production (www.gov.cn/xinwen/2018-08/31/content_5317931.htm accessed on 16 January 2022.). The literature also suggests that as a whole, China's pig sector still lags behind in terms of technical efficiency, despite the rising share of pig production from large modern pig farms in recent years. For example, Xu et al. [18] find that China's pig farms have an average technical efficiency of 0.6 (with 1 being the efficiency frontier); thus, there are large potential efficiency improvements to be realized.

5.2. Modeling Future Supply Scenarios

Based on the literature, we construct a set of counterfactual scenarios and conduct model simulations with the GTAP model to illustrate the potential impacts of adopting these supply side measures on China's pork markets. In the first scenario named FO (for "feed optimization"), an efficiency improvement is assumed to allow a per unit reduction in the feed used in the pig and poultry sector to track the two percentage point reduction in the protein contents of feed. This involves mainly feed derived from soybean and maize,

as well as other grains and crop products. In the second scenario named AY (for "attainable yields"), we assume land productivities in soybean and maize production to rise from the base case so as to eliminate the gaps between the actual and attainable yield levels, as reported by Liu et al. [43]. In the third scenario (short-named "AY_FR", for "attainable yields" and "fertilizer reduction"), in addition to the yield shocks to soybean and maize (as in scenario AY), fertilizer use in soybean and maize are reduced, also according to Liu et al. [43]. In the fourth scenario, AY_FR_FO, we combine the shocks contained in both scenarios AY_FR and FO. Lastly, in the fifth scenario named AY_FR_FO_TE, in addition to the shocks contained in scenario AY_FR_FO, we introduce a total productivity shock in the pork sector so as to halve the observed efficiency gaps reported in Xu et al. [18]. We summarize the five scenarios in Table 2. In the standard GTAP model, land allocation is governed by a constant elasticity of the transformation frontier, with the elasticity of transformation set at 1. In these simulations, we set this elasticity to 0.01, to minimize the shifts in sectoral land use so as to mimic the yield gains on the existing crop patterns according to Liu et al. [43].

Table 2. Scenario design: changes in the relevant variables in China, % from base case.

	FO	AY	AY_FR	AY_FR_FO	AY_FR_FO_TE
Technical efficiency in feed use by the poultry and pig sector	12.5	0	0	12.5	12.5
Land productivity in soy production	0	47.4	47.4	47.4	47.4
Land productivity in maize production	0	49.1	49.1	49.1	49.1
Fertilizer use per unit of soy produced	0	0	0	16.2	16.2
Fertilizer use per unit of maize produced	0	0	0	15.7	15.7
Aggregate technical efficiency in poultry and pig sector	0	0	0	0	33.3

Note: FO refers to the feed optimization; AY: attainable yields; AY_FR: attainable yields and fertilizer reduction; AY_FR_FO: attainable yields, fertilizer reduction, fertilizer reduction, and feed optimization; AY_FR_FO_TE: attainable yields, fertilizer reduction, fertilizer reduction, feed optimization, and technical efficiency improvement. Source: own interpretation of results from the literature.

The five scenarios are each formulated as a set of exogenous shocks to the GTAP model, using an aggregated version of the most recent GTAP 10 database as the base case [44]. The aggregated database consists of 12 countries/regions (including China and its main feed grain/oilseeds and pork suppliers, such as Brazil, USA, Canada, Germany, Spain, Denmark, Netherlands, as well as several aggregated regions) and 32 sectors (including all the agricultural and food sectors listed in the disaggregated GTAP database, as well as several more aggregated manufacturing and services sectors).

5.3. Simulation Results

The main simulation results from the five scenarios, expressed as percentage changes from the same base case, are reported in Table 3. The fact that all five scenarios are simulated from the same base makes it possible to conduct cross-scenario comparisons of the magnitudes of the results. Such comparisons also allow for understanding the individual effect due to each of the supply side measures. For example, while the individual effects of FO or AY are directly reported in the FO and AY scenario, the effects of FR are approximately the difference between the results obtained from the scenarios AY_FR and

AY. By including more than one supply measure in the last three scenarios, the combined effects of these supply measures can also be revealed.

Table 3. Simulation results: changes in domestic outputs and market prices, and total imports in China (% from base).

		FO	AY	AY_FR	AY_FR_FO	AY_FR_FO_TE
Domestic outputs	oilseeds (soybean)	−0.48	14.48	15.91	15.23	14.35
	coarse grains (maize)	−1.09	2.63	2.88	1.68	0.39
	pork and poultry	1.38	0.47	0.52	1.86	26.50
Domestic market prices	oilseeds (soybean)	−0.46	−16.68	−18.05	−18.23	−18.23
	coarse grains (maize)	−1.10	−19.57	−21.25	−21.51	−21.52
	pork and poultry	−2.13	−0.51	−0.55	−2.59	−22.74
Total imports	oilseeds (soybean)	−0.41	−9.34	−10.15	−10.39	−10.24
	coarse grains (maize)	−1.78	−15.23	−16.53	−17.43	−18.05
	pork and poultry	−6.84	−1.33	−1.41	−7.90	−53.39

Note: FO refers to the feed optimization; AY: attainable yields; AY_FR: attainable yields and fertilizer reduction; AY_FR_FO: attainable yields, fertilizer reduction, fertilizer reduction, and feed optimization; AY_FR_FO_TE: attainable yields, fertilizer reduction, fertilizer reduction, feed optimization, and technical efficiency improvement. Source: own simulation results.

In the FO scenario (column FO in Table 2), the simulation results suggest that reduced feed demand, due to feed optimization, leads to lowered domestic production of soybean and maize in China (by 0.5% and 1%, relative to the base case) and increased pork production by nearly 1.4%. At the same time, China's total imports of soybean, maize and pork all decrease. As pork imports into China have a very small share in China's total pork supply, the 1.4% rise in China's domestic production leads to a disproportionately larger drop in imports (by nearly 7%). In the AY scenario, eliminating the gaps between actual and attainable yields of soybean and maize boosts soybean and maize production, particularly for soybean. The much larger increase in soybean outputs (14.5%) as compared to maize (2.6%) is due to the relatively larger yield gap in soybean (hence, larger productivity improvement in the scenario) and the inter-crop relocations of resources towards soybean production. Rising outputs of soybean and maize also help the pork output to expand, although by a much small amount (about 0.5%), due to the dominant share of imported feed used in pig production. Lowered soybean and maize prices in China (by 16.7% and 19.6%, respectively) and increased domestic outputs help limit soybean and maize imports (by 9.3% and 15.2%, respectively), thereby reducing China's feed import dependency. When combined with reductions in per unit fertilizer use (as in the AY_FR scenario), domestic outputs increase more compared to the AY scenario alone. Consequently, domestic market prices and imports drop more.

In the AY_FR_FO scenario, slightly smaller increases in the soybean and maize outputs are reported, as compared to the AY_FR scenario. However, increased domestic supply and more efficient use of feed result in larger increases in pork outputs (1.9%) and larger reductions in pork imports (by 7.9%). These results suggest that eliminating soybean and maize yield gaps and improving feed efficiency can achieve the duel objective of reducing

feed and pork imports. In the AY_FR_FO_TE scenario, in addition to the other supply-side measures, technical inefficiency is halved in the pig and poultry sector. Simulation results from this scenario point to slightly smaller soybean and maize outputs (14.4% and 0.4%, respectively) as compared to the AY_FR_FO scenario; however, pork outputs increase by 26.5%, mainly due to the assumed efficiency improvement in pig production. This results in large drop of pork price in China and leads to 53.4% reduction in pork imports.

In summary, the simulation results illustrate the role of several key supply-side measures in tackling China's over-reliance on imported feed (particularly soybean) and in meeting its pork self-sufficiency goal. In particular, efforts to minimize the yield gaps in soybean and maize can directly reduce China's massive feed imports, which can also reduce the environmental pressure associated with deforestation in South America. However, this measure alone is not enough to abate China's massive appetite for pork imports. In contrast, without increasing feed imports, optimizing feed use can improve domestic pork outputs and reduce pork imports, but only to a quite limited extent. Improving the overall technical efficiency in the pork sector appears to be a more effective measure that can raise China's pork outputs and reduce its imports substantially.

6. Conclusions and Discussions

As the world's largest producer and consumer of pork, China has recently experienced a major hog cycle. This cycle can be traced to the gradual decline of sow and pig herds from 2013 that was accelerated by the ASF outbreaks in 2018, resulting in a drastic downturn that more than halved the country's sow and pig herds from the norm levels in late 2019. To make up for the domestic shortage of pork supply, China imported record high levels of pork; however, this proved to be insufficient to dampen the soaring domestic market prices. Ultimately, pork consumption contracted significantly, as expenditure on pork consumption is a major item on Chinese consumers' food budget. After China's pig production sharply declined in late 2019, a rapid rebound ensued, leading to a complete recovery in less than two years.

In this paper, we document both the effects of the ASF outbreak and the factors that have led to the rapid recovery of domestic production capacity and outputs in China. Through a description analysis of production, consumption and trade statistics, it appears that the downturn in China's pig production capacity (in terms of sow and pig herds) and outputs (in terms of slaughtered pigs) had already happened well before the ASF outbreaks and the pressure to imports had been built up ever since. This observation, which has not been sufficiently recognized in the literature, illustrates the important structural deficiencies in China's pig sector that need to be rectified. Recent data also suggest that China launched a strong response to the ASF outbreaks that paved the way for a rapid recovery in pig production and receding domestic market prices. This recovery has exceeded the expectations reflected in the recent literature (for example that of Ma et al. [11]). The underlying drivers of the strong recovery include rapid and strict reactions to the ASF outbreaks, a multiple-prong government initiative towards supporting the pig producers, de facto relaxations of some of the recently introduced environmental regulations, large increases in domestic investment, and a reorganization of the pig sector featuring more scale operations. All these measures contributed to supporting the fundamental determinants of sow and pig production, such as sow herds, capital, land, and labor. Additionally, the structural changes promoted by government authorities that favor large and more efficient producers appear to have helped in raising the sector's efficiency.

The V-shaped rebound from the depth of the ASF outbreaks has also resulted in some serious undesirable consequences, such as widespread economic losses in the pig sector in the second half of 2021, prompting discussions on exit strategies from the pig sector. Major pork exporters to the Chinese market are also facing uncertain future export opportunities in the coming period, due to lower market prices and weaker demand. This finding has so far not been discussed in the current literature, to the best of our knowledge. It also calls into question the long-term sustainability of China's recently declared 95% pork self-

sufficiency goal, considering the country's high dependencies on imported feed grains and oilseeds, inefficient feed use, and overall lack of technical efficiency in pork production.

The second contribution of the current study is, therefore, based on an exploratory model-based numerical simulation analysis that investigates the potential impacts of a set of supply side measures. This numerical analysis addresses some of the long-term sustainability issues, such as dependency on imported feed, domestic feed yield gaps, feed conversion efficiency, and technical efficiency in pig production, as identified in the literature but have not quantified through a formal economic model [12,13,17,18,43,45,46]. The results from our analysis suggest that yield improvement can substantially reduce the reliance on imported feed but it can only increase domestic pork production marginally, while technical efficiency improvement in pork production has the largest potential in boosting domestic pork production, followed by feed optimization. These results connect to several studies in the literature and provide some additional insights. For instance, our results on the increased domestic soybean and maize production due to yield improvement are smaller than those obtained by Liu et al. that are based on the same yield assumption [43]. This is due to the fact that our model considers world market linkages and domestic price effects (i.e., rising domestic outputs tend to elicit lower domestic market price, thus limiting expansion of domestic production; similarly, the presence of cheaper soybean and maize on the world market also limits the extent of output expansion in China). The result concerning the importance of efficiency improvement in pig production echoes the findings from Zhang et al. [12]. Finally, the projected feed and pork imports under various configurations of assumptions enriches the results obtained in earlier studies that rely on demand side drivers only [17].

Our findings have direct policy implications for the sustainable development of China's pig sector. *First*, given the apparent domestic resource constraints to meet the rising animal food demand in China and the political preference for maintaining domestic self-sufficiency targets for both pork and feed, our results clearly point to the need to actively resort to supply-side measures to boost productivities in not only the pig sector but also the feed sector. The investments needed for implementing such supply-side measures can be substantial and the commitments are likely to be long-term for such measures to take effect. *Second*, while short-term support from government authorities appears to have worked well in restoring production capacity, the policy initiatives do not appear to have sufficiently addressed the structural issues identified in this work and in earlier studies. For instance, direct financial and other assistances, while tackling the immediate market shortage successfully, appeared to amplify and prolong the cyclic movements of market supply and market prices. This again points to reconsiderations in future policy design that should favor measures that address long-term supply constraints and structural limitations, rather than focusing on short-term fixes. *Last* but not the least, the role of imports in supplementing domestic production should not be ignored. To this end, the recently declared 95% pork self-sufficiency target appears to be a pragmatic choice that does allow for sizable imports from other major pig producing countries. Maintaining a stable import regime and allowing imports to compete with domestic production on equal footing will provide an important "stabilizer" for the domestic pork market.

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Appendix A

Table A1. China's environmental laws and regulations.

Time	Issued By	Regulations	Specific Clauses on Livestock Production
1 January 2014	State Council [32]	Regulations on Prevention and Control of Pollution by Scaled Livestock and Poultry Breeding Industry	China's first regulatory document specifically aimed at the prevention and control of pollution for livestock and poultry breeding. Clarified the division criteria of prohibited areas, applicable objects (livestock and poultry farms, breeding communities), incentives and punishments.
1 January 2015	State Council [33]	Environmental Protection Law	Clarified the site selection, construction and management of livestock and poultry farms, breeding communities, and designated slaughtering enterprises should comply with relevant laws and regulations.
April 2015	State Council [34]	Water Pollution Prevention and Control Action Plan	Scientifically delineates the prohibited areas for livestock and poultry breeding. Before the end of 2017, closed or relocated livestock and poultry farms (communities) and specialized breeding households in the prohibited areas according to law, and the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta and other areas will be completed one year ahead of schedule.
August 2015	Ministry of Agriculture and Rural Affairs (MARA) [47]	Notice on Cooperating with the Delimitation of Prohibited Areas for Livestock and Poultry Breeding	Requires that the animal husbandry and veterinary administrative departments at all levels actively cooperate with the environmental protection department to do a good job in the delimitation of prohibited areas, and report the delimitation of prohibited areas in time.
November 2015	MARA [48]	Guiding Opinions on Promoting the Adjustment and Optimization of the Distribution of Pig Breeding in the Southern Water Network Area	Main producing counties should formulate a pig breeding plan. Local government closes or relocates large-scale pig farms according to law, and guides the transfer of pig breeding to non-overloaded areas.
May 2016	State Council [49]	Soil Ten Articles	Clearly and reasonably determine the layout and scale of livestock breeding, and strengthen the prevention and control of livestock breeding pollution.

Table A1. *Cont.*

Time	Issued By	Regulations	Specific Clauses on Livestock Production
November 2016	Ministry of Ecology and Environment (MEE) and MARA [35]	Technical Guidelines for Delimitation of Prohibited Areas for Livestock and Poultry Breeding	Basis for delineating prohibited areas throughout the country in the later period. Local environmental protection, agriculture and animal husbandry departments should follow the unified deployment of the local government, actively cooperate with relevant departments, and assist in the closure or relocation of existing farms that really need to be closed or relocated in the prohibited breeding area.
December 2016	State Council [50]	The 13th Five-year Ecological and Environmental Protection Planning	Before the end of 2017, all regions are required to close or relocate livestock and poultry farms (communities) and professional breeding households in prohibited areas according to law.
1 January 2018	State Council [51]	Environmental Protection Tax Law	An environmental tax will be levied on farmers with a herd of more than 500 pigs.
May 2018	MARA and MEE [52]	Implementation Plan for the Assessment of Resource Utilization of Livestock and Poultry Breeding Waste in 2017	The environmental governance of livestock and poultry breeding was included in the performance assessment of local governments, which further increased the intensity of environmental supervision.

Sources: authors' compilation. See reference list.

Table A2. Slaughtered pigs of large producers: 2016–2020 (million heads).

Corporate Producer	2016	2017	2018	2019	2020
Muyuan	3.11	7.24	11.01	10.25	18.12
Zhengbang	2.27	3.42	5.54	5.78	9.56
Wen's	6.60	19.04	22.29	18.52	9.55
New Hope Liuhe	1.17	2.40	2.55	3.55	8.29
Tianbang	0.58	1.01	2.17	2.45	3.08
COFCO	1.71	2.23	2.55	1.99	2.10
Aonong	0.11	0.22	0.42	0.40	1.35
Trs Group	0.14	0.54	0.68	0.84	1.02
Haid Group	0.32	0.46	0.70	0.74	0.98
Total	16.01	36.56	47.91	44.52	54.04

Sources: authors' compilation from various public data sets.

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